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Crosstalk in Multiconductor Microstrip Transmission Lines

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This document describes the theory of crosstalk in multiconductor microstrip transmission lines. Equations are used to describe the behavior of signals propagating in a transmission line and to estimate the magnitude of crosstalk in the line. Symmetric two-conductor lines are discussed first to illustrate the general theory of the multiple lines.

The results of the theoretical calculations and experiment show that the magnitude of crosstalk is a function of the following: (1) dielectric constants, (2) line geometry, (3) amplitude and rise time of the applied signal, and (4) termination of the line.

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PREFACE

The technique presented here could prove useful in the analysis of the transient characteristics of the crosstalk waveforms, the delay time of the signal paths, the loading effect, and the ringing due to reflections in a microstrip transmission line. This work may also provide some insight into the way the interconnections might affect any set of logic circuits. Anyone who is interested in determining the characteristic impedance, the line thickness, or the dielectric thickness of the microstrip transmission line should find the computer program in appendix B to be useful.

CONTENTS

FIGURES

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ABSTRACT

This document presents the theory of crosstalk in multiconductor microstrip transmission lines. Equations are used to describe the behavior of signals propagating in a transmission line and to estimate the magnitude of crosstalk in the line. Symmetric two-conductor lines are discussed first to illustrate the general theory of the multiple lines.

A circuit board containing six microstrip lines was designed and fabricated to conduct experimental measurements. This board was used to verify theoretical development and predictions by means of measured results. Circuit parameters such as the mutual capacitance and mutual inductance were considered in the circuit analysis.

The results of the theoretical calculations and experiment show that the magnitude of crosstalk is a function of dielectric constant, line geometry, amplitude and rise time of the applied signal, and termination of the line.

INTRODUCTION

BACKGROUND

The need for smaller size microwave integrated circuits has led to the development of the microstrip transmission line. A cross sectional view of a microstrip line is shown in figure 1. A microstrip transmission line is based on plane parallel conductors with a metalized strip and a ground plane separated by a solid dielectric substrate. Microstrip technology is primarily used because signals, at relatively high frequencies, cannot be routed and interfaced with components by using conventional printed circuit board techniques. The microstrip is also chosen because of the convenience of mounting the microwave solid state devices onto the microstrip board. Compared to a two-wire line as shown in figure 2, a basic microstrip line is a two-conductor transmission line obtained by inserting a thin dielectric slab between the two conductors.

Microstrip transmission lines are shown in figure 3. These lines are interconnection lines that transmit information from one point of the system to another. Mutual coupling exists between these parallel lines because of the close proximity to one another and the orientation of their aiding fields. Coupling between these lines in the same plane gives rise to a problem called "crosstalk."

Crosstalk is the coupling of undesired signals between nearby lines. When designing system interconnections, crosstalk must be taken into consideration. The magnitude of the crosstalk can become significantly large and may result in false switching of the digital circuits. It is desirable to predict the behavior of the waves that propagate along the line and to estimate the amount of crosstalk present. The predicted result can be used to determine, in advance, the severity of the interconnection noise in the circuit. With this knowledge, a designer can anticipate the dynamic behavior of the interconnection line and correct the layout problems and printed circuit boards interconnects accordingly.

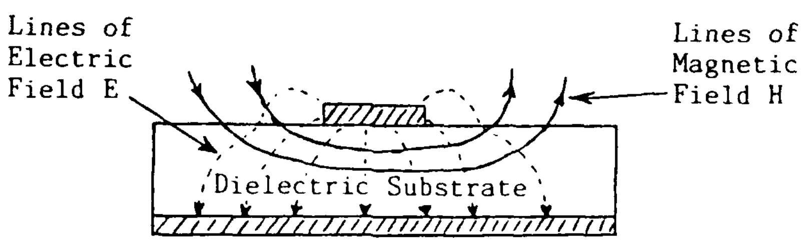


Figure 1. Cross sectional view of a microstrip line.

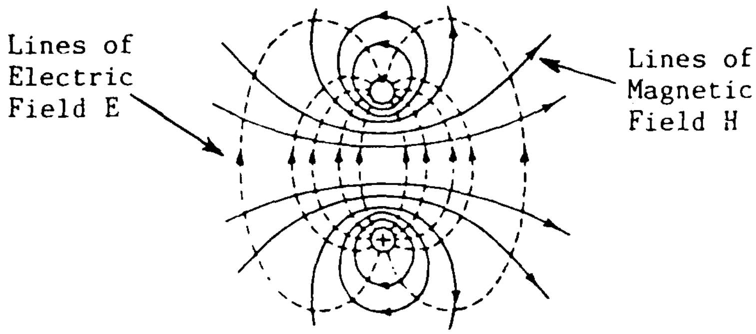


Figure 2. Cross sectional view of a two-wire line.

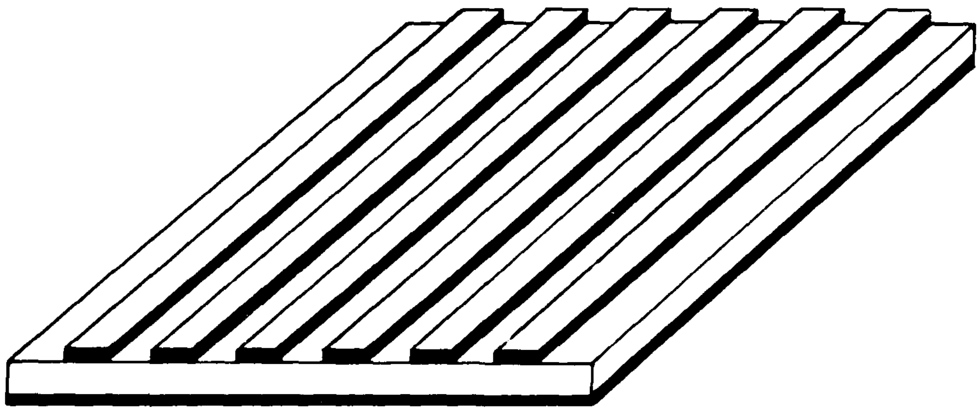


Figure 3. The microstr.p transmission line.

PROBLEM

The problem investigated in this study is the crosstalk in multiconductor microstrip transmission lines. When switching speed and packing density increase, the coupling of unwanted signals between nearby transmission lines (crosstalk) may increase and can result in interconnection noise and false switching of the digital logic circuits.

SCOPE

This thesis presents the analysis of crosstalk between parallel wires above a ground plane. Experiments using a single-layer printed circuit board were performed to verify the theoretical development. Factors contributing to the problem of crosstalk were determined by evaluating the time-domain response of the multiconductor transmission lines. An analytical approach is presented to predict the magnitude and the severity of crosstalk that is typical in electronic digital systems.

ASSUMPTIONS

The following assumptions and approximations were made in the analysis to simplify the theoretical presentation of the thesis:

1. The parallel conductors used in the analysis have zero or negligible resistances.
2. The multiconductor transmission line is considered to be uniform along its length.
3. The line behavior can be described in terms of inductances, capacitances, and conductances per unit length.
4. The wave propagation along the transmission line is of a quasi-transverse electromagnetic (TEM) nature [1, 2, 3, 4].
5. The case of weak coupling is considered so that the effect on line one (figure 4) of any voltages and currents induced in nearby lines is negligible and can be ignored.

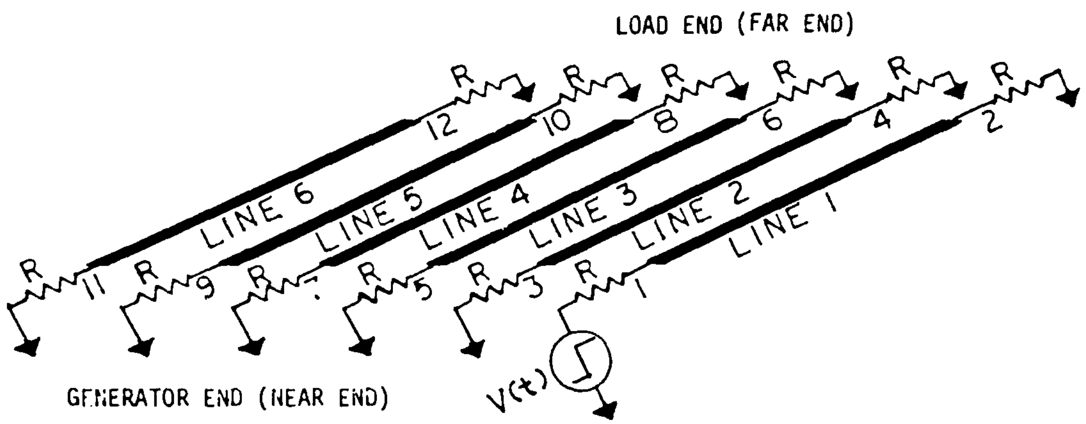


Figure 4. Circuit showing a known voltage applied to port 1 at the generator end.

APPROACH

Laplace transforms and a system of partial differential equations were used to derive the equations of the transmission lines.

An experiment was conducted to illustrate the theoretical principles: given a multiconductor microstrip transmission line, a known voltage was applied to one of the ports, figure 4. The remaining ports were terminated by load resistances.

Measurements were made at the various points in the system, such as the generator end (near end) and the load end (far end), to determine any traces of crosstalk or transient response between the lines. The following conditions were investigated to determine their effect on the crosstalk:

1. changing some of the values of the load resistance R in the circuit
2. increasing the separation between the lines
3. effectively varying the length of the lines
4. varying the applied voltage V(t)

THEORETICAL DEVELOPMENT

BASIC TRANSMISSION LINES

A transmission line is essentially a system of material boundaries forming a continuous path from one place to another and capable of directing the transmission of electromagnetic energy along this path [5]. A transmission line can be represented by the following parameters: series inductance, series resistance, shunt capacitance, and shunt conductance. This is shown in figure 5.

This transmission line can be characterized by the numerical values of its parameters per unit length, i.e.,

L = Inductance in Henrys per unit length

R = Resistance in Ohms per unit length

C = Capacitance in Farads per unit length

G = Conductance in Mhos per unit length.

If one considers a differential length of transmission line (see figure 6), then the two basic transmission line equations can be written by inspection [6]:

$$\frac{\partial V}{\partial X} = L \frac{\partial I}{\partial t} + RI \tag{1}$$

$$-\frac{\partial I}{\partial X} = C \frac{\partial V}{\partial t} + GV, \tag{2}$$

where

I = Current

V = Voltage.

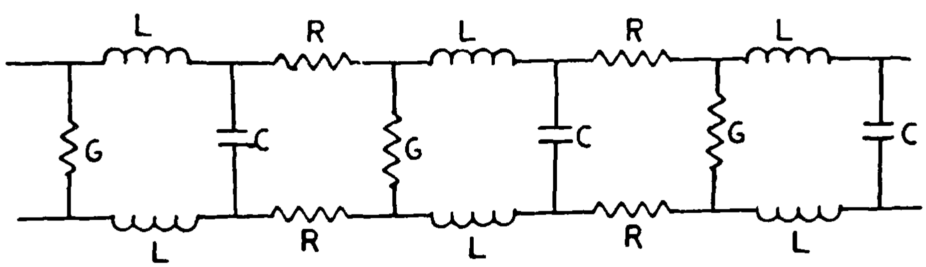


Figure 5. Transmission line and its parameters.

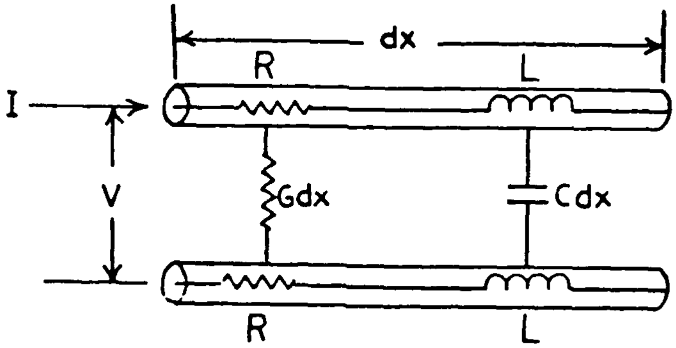


Figure 6. Differential length of transmission line.

The equations for lossless transmission lines are obtained from equations (1) and (2) by setting R = G = 0:

$$-\frac{\partial V}{\partial X} = L\frac{\partial I}{\partial t} \tag{3}$$

$$-\frac{\partial I}{\partial X} = C\frac{\partial V}{\partial t}\ . \tag{4}$$

Differentiating equation (3) with respect to x gives

$$-\frac{\partial^2 V}{\partial X^2} = L\frac{\partial^2 I}{\partial t \partial X}\ . \tag{5}$$

Differentiating equation (4) with respect to t gives

$$-\frac{\partial^2 I}{\partial X \partial t} = C\frac{\partial^2 V}{\partial t^2}\ . \tag{6}$$

Substituting equation (5) into (6) gives

$$-\frac{\partial^2 V}{\partial X^2} = LC\frac{\partial^2 V}{\partial t^2}\ . \tag{7}$$

Using similar approach, equations (3) and (4) may be differentiated with respect to t and to x, respectively, to obtain the expression for current

$$\frac{\partial^2 I}{\partial X^2} = LC\frac{\partial^2 I}{\partial t^2}\ . \tag{8}$$

Equations (7) and (8) are in the form of a one-dimensional wave equation [7]:

$$\frac{\partial^2 Y}{\partial X^2} = \frac{1}{\mu^2} \frac{\partial^2 Y}{\partial t^2} , \tag{9}$$

where μ is the velocity of propagation.

Comparing equations (9) and (7), the constant μ is related to known parameters L and C by the expression

$$\mu = \frac{1}{\sqrt{LC}} \tag{10}$$

$$= \frac{1}{T_D} ,$$

where T_D = delay, the time a signal needs to travel a unit length of the transmission line.

WAVE PROPAGATION IN TRANSMISSION LINES

The solutions of the wave equations (7) and (8) can be written in the following general forms [6]:

$$V(X,t) = V^+\left(t - \frac{X}{\mu}\right) + V^-\left(t + \frac{X}{\mu}\right) \tag{11}$$

$$I(X,t) = \frac{V^+\left(t - \frac{X}{\mu}\right)}{R_o} - \frac{V^-\left(t + \frac{X}{\mu}\right)}{R_o} , \tag{12}$$

where R_o = characteristic resistance of the line.

The first terms of equations (11) and (12) represent the traveling waves that travel in the positive x direction (incident wave).

Figure 7 shows a transmission line terminated with a load resistance R_L. If the reference point for x is shifted to the position of the termination, the voltage and current at the load are related by

$$V(0,t) = R_L \, I(0,t) . \tag{13}$$

If the characteristic resistance R_o does not match the load resistance R_L, the incident wave is reflected from the load resistance. This fraction of the voltage reflected is called the voltage reflection coefficient ρ_L. That is,

$$V^-(0,t) = \rho_L \, V^+(0,t) , \tag{14}$$

where $V^-(0,t)$ = reflected voltage at the termination point and $V^+(0,t)$ = incident voltage at the termination point. The total voltage at the termination point is

$$V(0,t) = V^+(0,t) + V^-(0,t) . \tag{15}$$

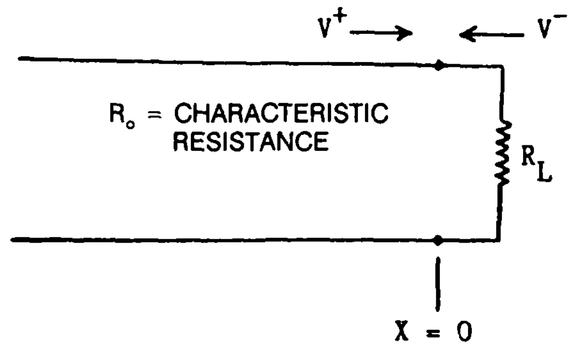


Figure 7. Terminated line with reference x shifted.

Substituting equation (14) to equation (15) gives

$$V(0,t) = V^+(0,t) + \rho_L V^+(0,t)$$

$$= V^+(0,t)[1 + \rho_L] \; . \tag{16}$$

Similarly, for current

$$I(0,t) = \frac{V^+(0,t)}{R_o} - \frac{V^+(0,t)}{R_o}$$

$$= \frac{V^+(0,t)}{R_o} - \frac{\rho_L V^+(0,t)}{R_o}$$

$$= \frac{1}{R_o}[V^+(0,t) - \rho_L V^+(0,t)]$$

$$= \frac{V^+(0,t)}{R_o}[1 - \rho_L] \; . \tag{17}$$

At the load or termination point, then

$$\frac{V(0,t)}{I(0,t)} = R_L = \frac{V^+(0,t)[1 + \rho_L]}{\frac{V^+(0,t)[1 - \rho_L]}{R_o}}$$

or

$$\frac{R_L}{R_o} = \frac{1 + \rho_L}{1 - \rho_L} \; . \tag{18}$$

Solving for the voltage reflection coefficient,

$$\rho_L = \frac{R_L - R_o}{R_L + R_o} \tag{19}$$

where ρ_L = load reflection coefficient.

One may consider a general case of the transmission line when both the resistance of the source R_s and the resistance of the load R_ℓ are different from the characteristic resistance. Figure 8 shows the general case of the transmission line.

The lossless transmission line is characterized by its time delay T_D and its characteristic impedance R_o. As shown in equation (10), T_D is a function of inductance L and capacitance C. These parameters are functions of physical and electrical properties such as thickness, spacing, and dielectric constant. All of these factors determine the behavior of the signals on a transmission line. An understanding of the behavior of these signals is significant for determining the methods used to terminate these lines.

The voltage reflection coefficient at the load end of the transmission line depends on the load impedance and the characteristic impedance as was shown by equation (19), i.e.,

$$\rho_L = \frac{R_L - R_o}{R_L + R_o} .$$

Signal travels to the load with a velocity μ and reaches the load side T_D time later. If R_o does not match the R_L, the signal is reflected; however, if $R_L = R_o$ there is no reflection. This reflected signal from the load travels back toward the source and reaches the source at time $2T_D$. Again, because of the mismatch in the resistance of R_o and R_s, the signal is reflected there in the same fashion as at the load by the sending end reflection coefficient ρs.

$$\rho_s = \frac{R_s - R_o}{R_s + R_o} \tag{20}$$

where Rs = sending end resistance.

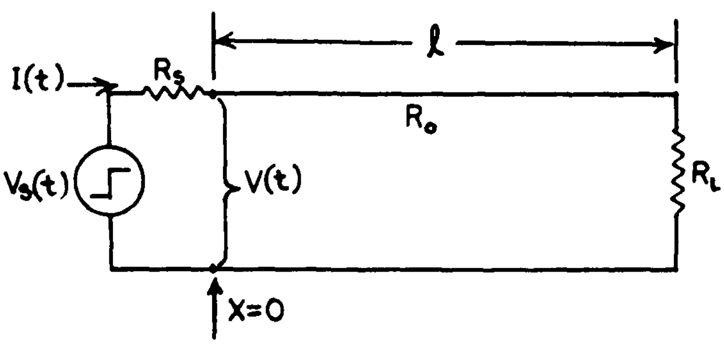


Figure 8. General case of transmission line.

This back and forth reflection process of the traveling wave between the source and the load end of the line successively reduces the signal by the reflection coefficients and if the line is lossy, by the resistance of the line.

The reflected voltage at the input end (after the leading edge of the incident wave has traveled the entire length of the line, been reflected at the load, and has returned to the source end) is

$$V^{+}\left(\frac{2\ell}{\mu}\right) = Vs\left(\frac{2\ell}{\mu}\right)\left[\frac{R_o}{R_o + R_s}\right] + V^{-}\left(\frac{2\ell}{\mu}\right)\left[\frac{R_s - R_o}{R_s + R_o}\right]. \tag{21}$$

The derivation of this equation is presented in Appendix A1.

THE MICROSTRIP TRANSMISSION LINE

The microstrip transmission line is the most common type of planar transmission structure for interconnecting high-speed circuits. It can be fabricated in the form of printed circuit boards to provide uniform signal paths. The cross sectional view of a microstrip line is shown in figure 9. The signal lines are made in an entire board by etching away the unwanted copper from between the strip conductors using photo resist techniques.

If the thickness(t), width(w) of the strip conductor, and the distance(h) from the ground plane are controlled, the line will exhibit a predictable characteristic impedance.

The characteristic impedance, Z_o, of this microstrip line is [8, 9]:

$$Z_o = \frac{87}{\sqrt{\epsilon_r + 1.41}} \ln\left[\frac{5.98\ h}{0.8\ w + t}\right] \tag{22}$$

for

$$0.1 \leq \frac{w}{h} \leq 3 \quad \text{and} \quad 1 \leq \epsilon_r \leq 15.$$

Here ϵ_r = relative dielectric constant of the board material

w = width of the line (line width)

t = thickness of the line (copper thickness), and

h = dielectric thickness.

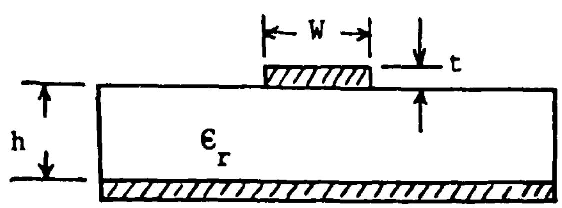


Figure 9. Cross sectional view of a microstrip line.

A computer program was developed to determine the values of the characteristic impedance, line width, copper thickness, or dielectric thickness. This program also provides the ability to use other materials and geometries of the microstrip transmission line.

The characteristic impedance of the microstrip line was calculated using this program and is listed in tables 1, 2 and 3. The tables show the characteristic impedance of the microstrip line for various geometries and for a given dielectric constant of 4.7. The values listed in the tables were plotted in figures 10a, 10b, and 10c and closely agree with the experimental time domain reflectometer measurements.

Table 1. Characteristic impedance as a function of line width. $\epsilon_r = 4.7$, h = 0.062 inch, t = 0.002 inch.

	w, Line Width (MILS)	Z, Impedance (OHMS)
1	10	127.16
2	15	115.32
3	20	106.48
4	25	99.41
5	30	93.53
6	35	88.49
7	40	84.09
8	45	80.17
9	50	76.65
10	55	73.45
11	60	70.52
12	65	67.81
13	70	65.29
14	75	62.95
15	80	60.75
16	85	58.68
17	90	56.72
18	95	54.87
19	100	53.11
20	105	51.43
21	110	49.83
22	115	48.30
23	120	46.83

Table 2. Characteristic impedance as a function of dielectric thickness. $\epsilon_r = 4.7$, w = 0.109 inch, t = 0.002 inch.

	h, Dielectric Thickness (MILS)	Z, Impedance (OHMS)
1	40	34.72
2	45	38.86
3	50	42.57
4	55	45.93
5	60	48.99
6	65	51.81
7	70	54.14
8	75	56.84
9	80	59.12
10	85	61.25
11	90	63.26
12	95	65.16
13	100	66.97
14	105	68.69
15	110	70.32
16	115	71.89
17	120	73.39
18	125	74.82
19	130	76.20

Table 3. Characteristic impedance as a function of copper thickness. ϵ_r = 4.7, w = 0.109 inch, h = 0.062 inch.

	t, Copper Thickness (MILS)	Z, Impedance (OHMS)
1	0.5	50.74
2	1.0	50.54
3	1.5	50.34
4	2.0	50.14
5	2.5	49.95
6	3.0	49.75
7	3.5	49.56
8	4.0	49.36
9	4.5	49.17
10	5.0	48.98

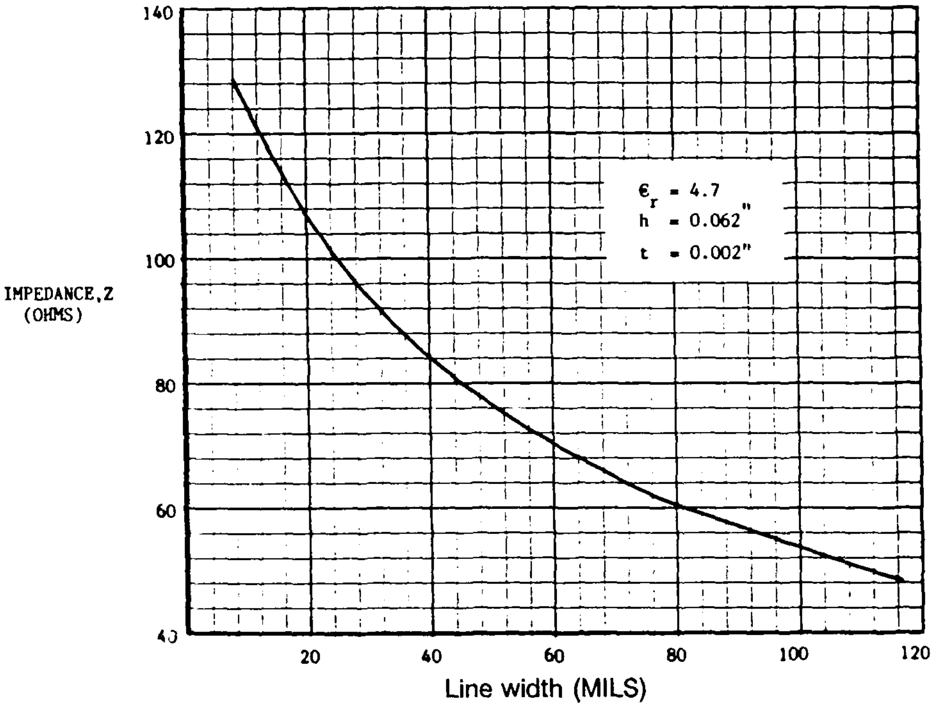


Figure 10a. Impedance versus line width for microstrip transmission line.

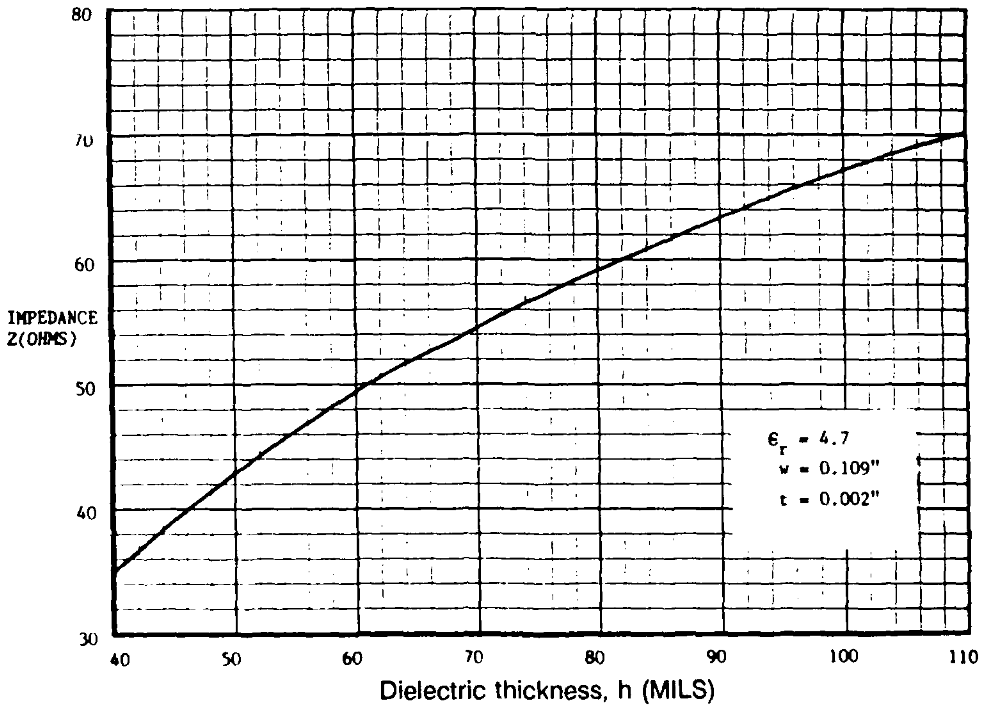


Fig. - 10b. Impedance versus dielectric thickness for microstrip transmission line.

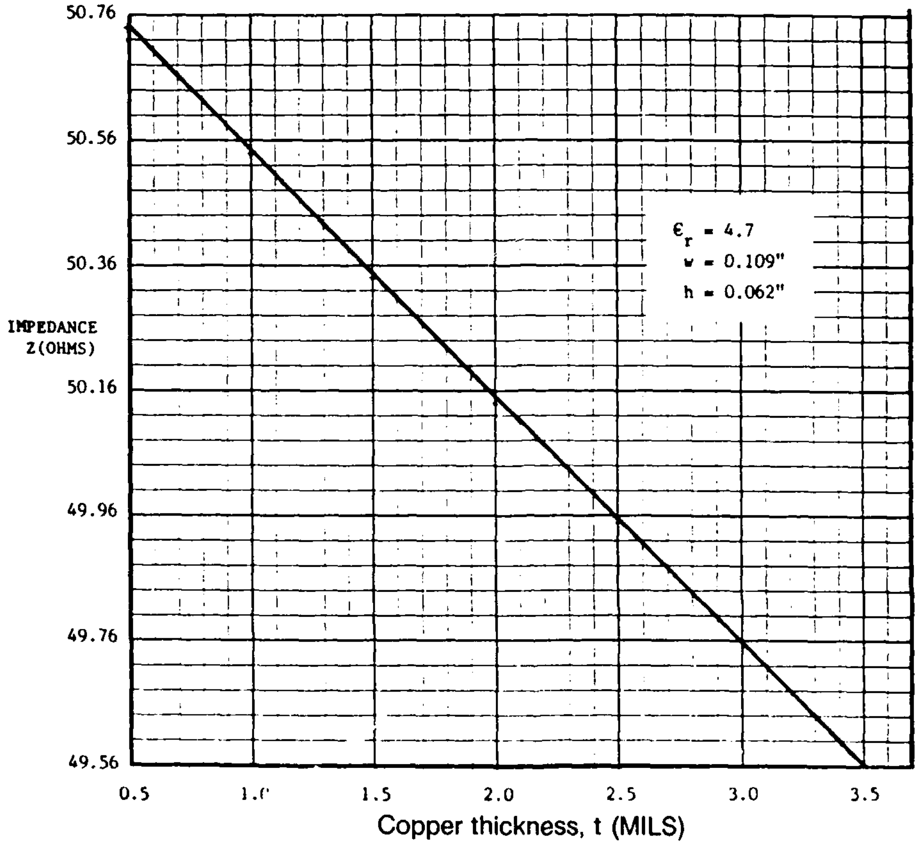


Figure 10c. Impedance versus line thickness for microstrip transmission line.

Figure 11 shows the inductance per foot as a function of characteristic impedance and capacitance per foot of the line. The inductance per foot is calculated as

$$L = C\,Z^2 \tag{23}$$

where

L = inductance per foot

Z = characteristic impedance

C = capacitance per foot.

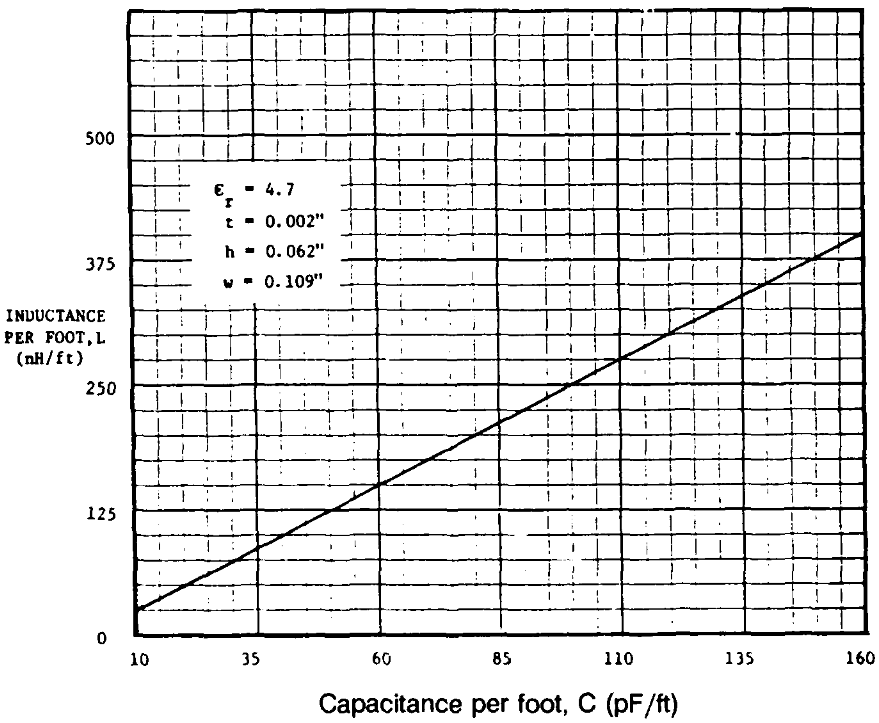


Figure 11. Inductance versus capacitance for microstrip transmission line with characteristic impedance of 50 ohms.

Values of the inductance per foot were calculated using equation 23 and were listed in table 4.

The propagation delay of the microstrip transmission line is dependent only on the dielectric constant of the board and is not a function of line width or the dielectric thickness. For a microstrip transmission with a given relative dielectric constant, the propagation delay of the line may be calculated by [10]

$$T_D = 1.017\sqrt{0.475\,\epsilon_r + 0.67} \quad \text{ns/ft}\,. \tag{24}$$

For G-10 fiber glass epoxy boards, the propagation delay of the microstrip line is calculated to be 1.77 ns/ft.

Table 4. Inductance as a function of capacitance $\epsilon_r = 4.7$, $w = 0.109$ inch, $h = 0.062$ inch, $t = 0.002$ inch.

	Inductance per foot, L (nH/ft) $L = C Z^2$	Capacitance per foot, C (pF/ft)
1	25	10
2	50	20
3	75	30
4	100	40
5	125	50
6	150	60
7	175	70
8	200	80
9	225	90
10	250	100
11	275	110
12	300	120
13	325	130
14	350	140
15	375	150
16	400	160

CROSSTALK BETWEEN TRANSMISSION LINES

The microstrip lines are short-circuit conductors to very low frequency signals; however, at very high speeds, these lines act as transmission lines. Fast logic gates can generate high speed signals that can make the circuit interconnections take on the appearance of transmission lines. These transmission lines when placed in close proximity to one another introduce the problem of crosstalk.

Crosstalk is the coupling of unwanted signals between the nearby transmission lines. It causes digital system noise that introduces false information and results in false switching in high speed digital systems.

Coupling is caused by capacitance between the lines, mutual capacitance, C_m and mutual inductance, L_m. Figure 12 shows the line parameters and crosstalk coupling in parallel lines of a microstrip transmission line.

When a signal pulse propagating along line 1 reaches any arbitrary point x, the signal is capacitively coupled into line 2 (figure 12). The coupled voltage on line 2 causes current to flow from the point of coupling, point Y, to both ends of the line.

This current divides and results in voltage traveling towards the load end (forward wave) and voltage traveling towards the generator end (backward wave). At the same point of coupling, point Y, the mutual inductance of the parallel line also couples current into line 2 in the direction of the generator end. Since the dominant effect in the parallel line coupling is primarily inductive, a positive-going wave traveling on line 1 produces a negative-voltage wave on line 2.

Using equation 3 and 4, one can determine the partial differential equation of the voltage and current in line 1 of figure 12.

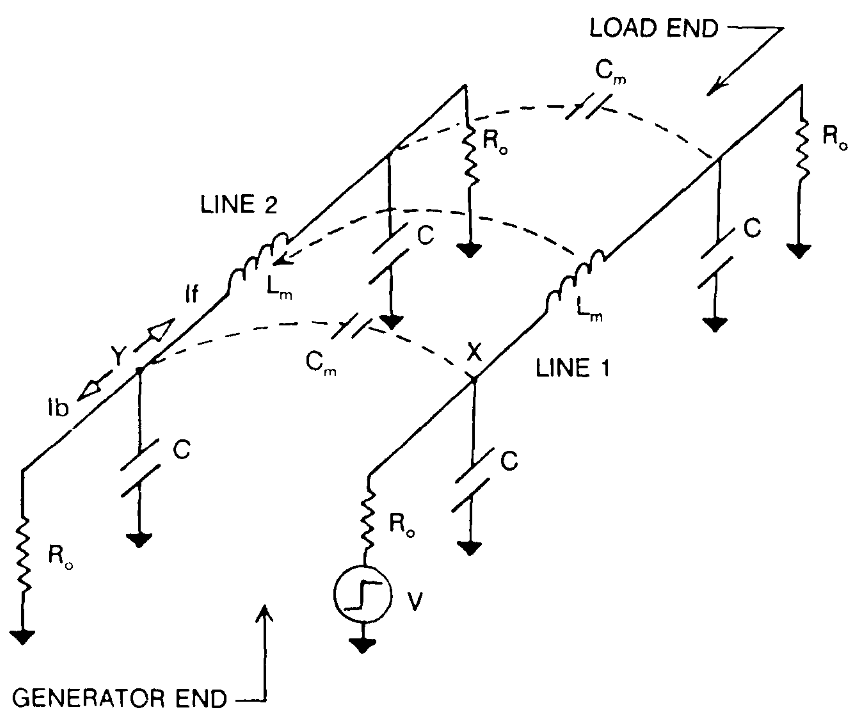


Figure 12. Line parameters and crosstalk coupling in parallel lines.

$$-\frac{\partial I_1}{\partial X} = C\,\frac{\partial V_1}{\partial t}\,. \tag{25}$$

$$-\frac{\partial V_1}{\partial X} = L\,\frac{\partial I_1}{\partial t}\,, \tag{26}$$

where V_1 = voltage in line 1

and I_1 = current in line 1.

The partial differential equations describing the mutual coupling between parallel lines of figure 12 are [11]

$$-\frac{\partial I_2}{\partial X} = C\,\frac{\partial V_2}{\partial t} - C_m\,\frac{\partial V_1}{\partial t} \tag{27}$$

$$-\frac{\partial V_2}{\partial X} = L\,\frac{\partial I_2}{\partial t} + L_m\,\frac{\partial I_1}{\partial t}\,, \tag{28}$$

where

C = Capacitance per unit length

C_m = mutual capacitance per unit length

L = inductance per unit length

L_m = mutual inductance per unit length

V_1, I_1 = voltage and current in line 1

and

V_2, I_2 = voltage and current in line 2.

Equations 32 through 35 are the differential equations of the system and valid only for a TEM mode of propagation and for a system with weak coupling. Using equation 7, one can obtain the wave equation on line 1.

$$\frac{\partial^2 V_1}{\partial X^2} = LC\,\frac{\partial^2 V_1}{\partial t^2}\,,$$

since

$$LC = \frac{1}{\mu^2}$$

then

$$\frac{\partial^2 V_1}{\partial X^2} = \frac{1}{\mu^2}\frac{\partial^2 V_1}{\partial t^2} . \tag{29}$$

Taking Laplace transform of equation 29 gives the Laplace transform of traveling waves on line 1:

$$\frac{\partial^2 \mathcal{L} V_1}{\partial X^2} = \frac{1}{\mu^2} s^2 \mathcal{L} V_1 . \tag{30}$$

The Laplace transform of traveling wave on line 2 is [cf Appendix A2]

$$\frac{\partial^2 \mathcal{L} V_2}{\partial X^2} - \frac{s^2 \mathcal{L} V_2}{\mu^2} = \frac{s^2 \mathcal{L} V_1}{\mu^2} \gamma(K - 1) . \tag{31}$$

Reference 11 has shown the solution to equations 30 and 31. If lines of length ℓ are terminated in their characteristic impedance Z_0 and a voltage V is applied to the input of line 1 (figure 12), we have [reference 11]

$$\mathcal{L} V_1 = \mathcal{L} V e^{-s\left(\frac{X}{\mu}\right)} , \tag{32}$$

$$Z_0 \mathcal{L} I_1 = \mathcal{L} V e^{-s\left(\frac{X}{\mu}\right)} , \tag{33}$$

$$\mathcal{L} V_2 = \gamma \mathcal{L} \; \frac{V}{2} \left[e^{-s\left(\frac{X}{\mu}\right)} - e^{-s\left(\frac{2\ell - X}{\mu}\right)} \right] \left[\frac{(K + 1)}{2}\right] - \left[\frac{\gamma(K - 1)}{2}\right] \left(\frac{X}{\mu}\right) (s\mathcal{L}V) e^{-s\left(\frac{X}{\mu}\right)} , \tag{34}$$

$$Z_0 \mathcal{L} I_2 = \gamma \mathcal{L} \; \frac{V}{2} \left[-e^{-s\left(\frac{X}{\mu}\right)} + e^{-s\left(\frac{2\ell - X}{\mu}\right)} \right] \left[\frac{(K + 1)}{2}\right] - \left[\frac{\gamma(K - 1)}{2}\right] \left(\frac{X}{\mu}\right) (s\mathcal{L}V) e^{-s\left(\frac{X}{\mu}\right)} . \tag{35}$$

Taking the inverse Laplace transform of equation 32 and 33 we get

$$V_1 = V \cdot u\left(t - \frac{X}{\mu}\right) \tag{36}$$

$$Z_0 I_1 = V \cdot u\left(t - \frac{X}{\mu}\right) , \tag{37}$$

where $u(t - x/\mu)$ = a unit step function occurring at $t = x/\mu$.

Taking the inverse Laplace transform of equation 34 we have

$$V_2 = \gamma\, \frac{V}{2} \left\{ u\left(t - \frac{X}{\mu}\right) - u\left[t - \frac{(2\ell - X)}{\mu}\right] \right\} \left(\frac{K+1}{2}\right) - \gamma\left(\frac{K-1}{2}\right)\left(\frac{X}{\mu}\right)\left(\frac{dV}{dt}\right) \cdot u\left(t - \frac{X}{\mu}\right). \tag{38}$$

If x = 0 we can calculate the backward crosstalk (V_{bx}) wave at the generator end of line 2

$$V_{bx} = \left[\frac{\gamma(K+1)}{2}\right]\left(\frac{V}{2}\right)\left[u\left(t - \frac{X}{\mu}\right) - u\left(t - \frac{2\ell}{\mu}\right)\right], \tag{39}$$

where

$u(t - 2\ell/u)$ = a unit step function occurring at $t = 2\ell/u$

and

$\gamma(K + 1)/2$ = backward crosstalk constant, Kb.

Taking the inverse Laplace transform of equation 35 we have

$$Z_o I_2 = \gamma\, \frac{V}{2} \left\{ -u\left(t - \frac{X}{\mu}\right) + u\left[t - \frac{(2\ell - X)}{\mu}\right] \right\} \left(\frac{K+1}{2}\right) - \gamma\left(\frac{K-1}{2}\right)\left(\frac{X}{\mu}\right)\left(\frac{dV}{dt}\right) \cdot u\left(t - \frac{X}{\mu}\right), \tag{40}$$

if $x = \ell$, we can calculate the forward crosstalk wave at the load end of line 2

$$V_{fx} = -\left[\frac{\gamma(K-1)}{\mu}\right]\left(\frac{\ell}{2}\right)\left(\frac{dV}{dt}\right) \cdot u\left(t - \frac{\ell}{\mu}\right), \tag{41}$$

where

$u(t - \ell/u)$ = a unit step function occurring a $t = \ell/\mu$

and

$\gamma(K - 1)/\mu$ = forward crosstalk constant, K_f.

Equations 38 through 41 show that the induced waves on line 2 are of two modes: backward crosstalk and forward crosstalk. Forward crosstalk is the forward-traveling wave propagating towards the load end of the line. As shown in equation 41, the magnitude of the forward crosstalk (Vf) is

$$V_f = -\left[\frac{\gamma(K-1)}{\mu}\right]\left(\frac{\ell}{2}\right)\left(\frac{dV}{dt}\right). \tag{42}$$

Equation 42 can also be expressed in terms of mutual inductance, mutual capacitance and characteristic impedance (appendix A3)

$$V_f = \left(C_m Z_o - \frac{L_m}{Z_o} \right) \left(\frac{\ell}{2} \right) \left(\frac{dV}{dt} \right) , \tag{43}$$

where

$$Z_o = \sqrt{\frac{L}{C}} ,$$

characteristic impedance.

In terms of transit time T for the transmission line, equation 43 can be expressed as [appendix A4]

$$V_f = \left(\frac{C_m}{C} - \frac{L_m}{L} \right) (T) \left(\frac{1}{2} \right) \left(\frac{dV}{dt} \right) , \tag{44}$$

where

$T = \ell \sqrt{LC}$, Transit time.

The forward crosstalk constant (K_f) is used to predict the forward crosstalk in the transmission line. Figure 13 shows the curve of $\gamma(K - 1)/\mu$ *as a function of the spacing (s)* between the lines and the height (h) of the lines above the ground plane.

Therefore, the forward crosstalk is dependent upon the line geometry which influences values for C_m, L_m, C, the length of the line transmission line, and the time differential of the signal on line 1. The amplitude of the induced wave is also proportional to the transit time along the line.

Backward crosstalk is the backward-traveling wave propagating towards the source. It has the same form as the input signal. As shown in equation 39, the magnitude of the backward crosstalk (V_b) is

$$V_b = \left[\frac{\gamma(K + 1)}{2} \right] \left(\frac{V}{2} \right) . \tag{45}$$

In terms of mutual capacitance, mutual inductance and characteristic impedance, equation 45 can be expressed as (appendix A5)

$$V_b = \left(\frac{V}{4} \right) \left(\frac{L_m}{Z_o} + C_m Z_o \right) . \tag{46}$$

Again, the factor $[\gamma(K + 1)/2]$ is the backward crosstalk constant (K_b) and it is used to predict the backward crosstalk in the transmission line. Figure 14 is the curve of $[\gamma(K + 1)/2]$ as a function of the line spacing and height. Figures 13 and 14 are curves for microstrip lines with relative dielectric constant of 4.7.

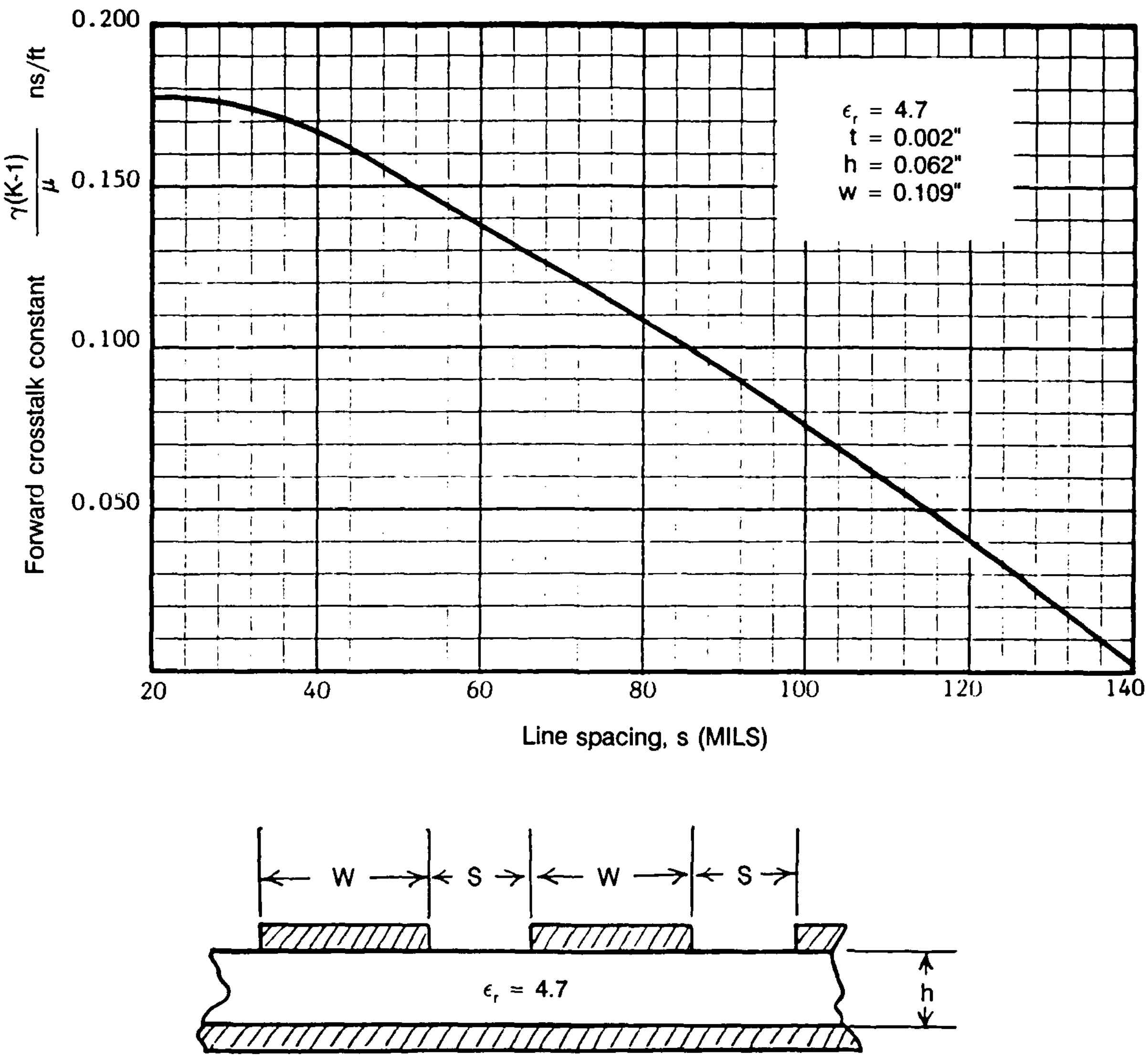
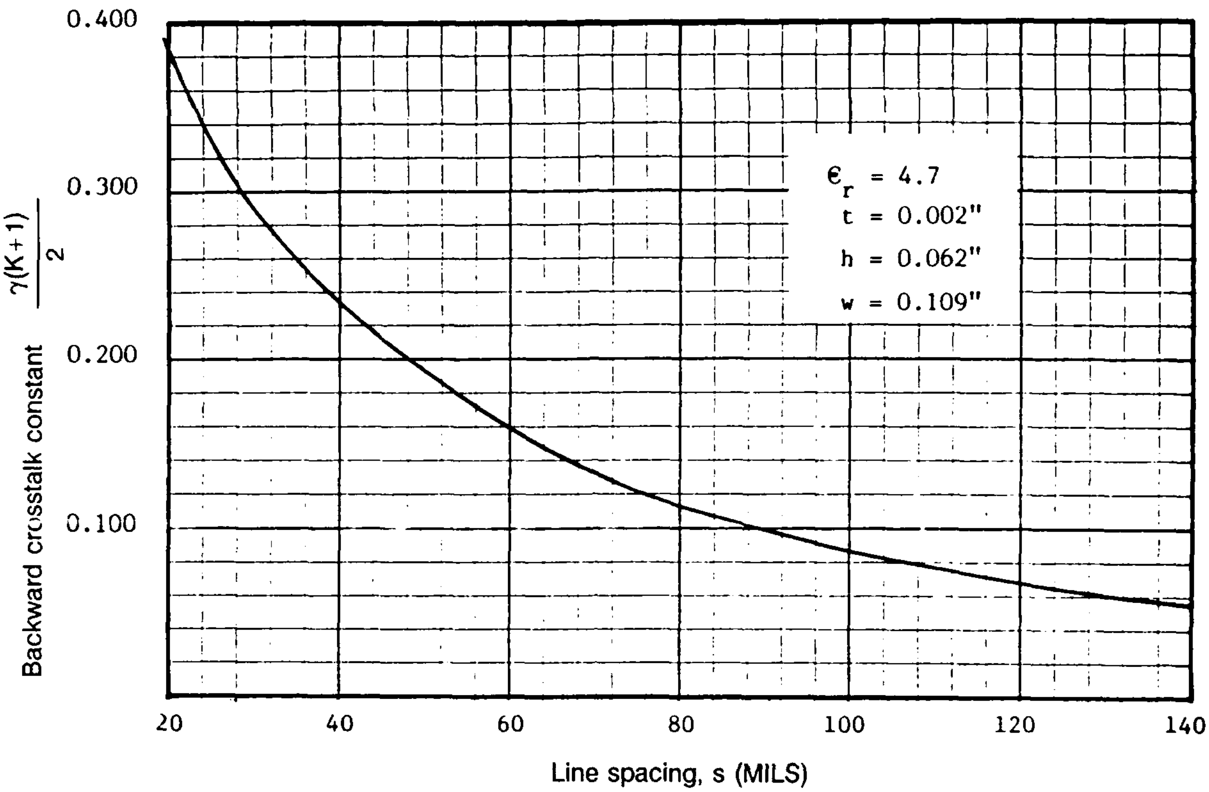


Figure 13. Forward crosstalk versus line spacing for microstrip line on glass epoxy boards with ϵ_r = 4.7.



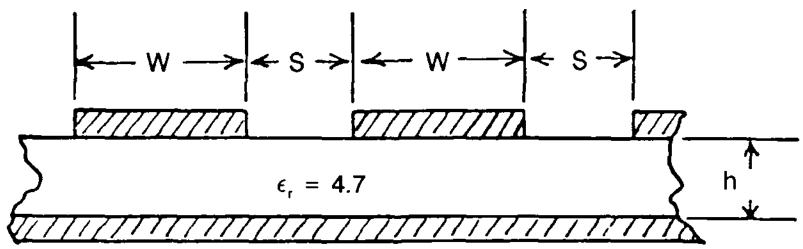


Figure 14. Backward crosstalk constant versus line spacing for microstrip lines on glass epoxy boards $\epsilon_r = 4.7$.

THEORETICAL PREDICTIONS

The response of the printed transmission line is predicted theoretically from equations 39 and 41. Along with these equations, figures 13 and 14 are conveniently used to determine the amplitude of the backward wave and the forward wave.

With known amplitude of the applied signal, signal rise time, and crosstalk constants, the magnitude of the crosstalk induced in the adjacent line is calculated as shown in appendix C1 through C3 (sample calculations). The method used in the calculation assumes that signal rise time (tr) is less than twice the electrical delay of the line, i.e., $tr < 2\ell/\mu$. The time delay of the transmission line must be longer than the signal rise time so that reflections will appear at their full amplitude. If the electrical delay of the line is much greater than the rise time, i.e., $tr >> 2\ell/\mu$, the crosstalk will fail to achieve maximum amplitude. In this case, the crosstalk amplitude should be multiplied by a factor $2\ell/\mu(tr)$ to obtain the correct value of the crosstalk amplitude.

EXPERIMENTAL SET-UP

The purpose of this experiment is to demonstrate the theory discussed previously and to gain better insight into how the applied signal, line geometry, and other parameters affect the crosstalk between adjacent lines. In each experiment, the observed waveforms were measured, recorded, and photographed. The measurements were obtained using the experimental system shown in figure 15. A controllable rise and fall waveform was generated by a Tektronix, PG 508, 50 MHz pulse generator. Its output was applied to one of the ports of the conductors in the microstrip transmission line, figure 16. The voltage waveforms were measured from the various ports of the line using a Tektronix 2465A, 350 MHz oscilloscope. The printed circuit board used in this experiment is constructed of copper and glass epoxy with a relative dielectric constant $\epsilon_r = 4.7$. The dimensions of the board and the microstrip transmission line are illustrated in figure 17. As shown in the figure, the microstrip lines are divided into group 1 and group 2. Both groups have the same line width; however, the line spacing of group 2 is twice that of group 1. Using equation 22, or the computer program in appendix B, the computed characteristic impedance of this fabricated board is 50.14 ohms (appendix B).

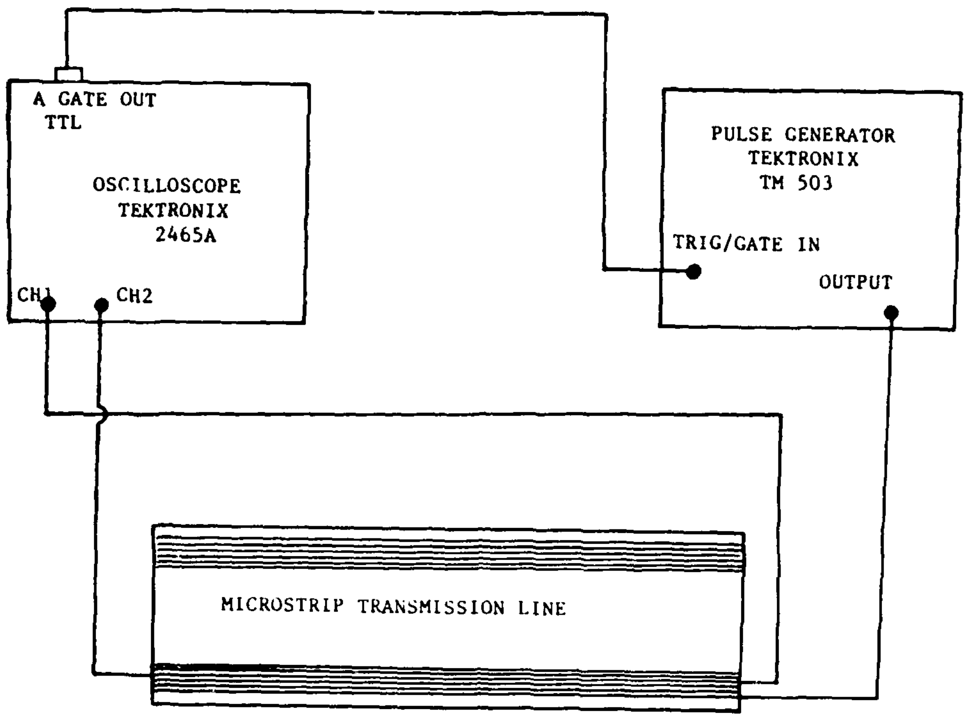


Figure 15. Experimental system used to obtain crosstalk measurements.

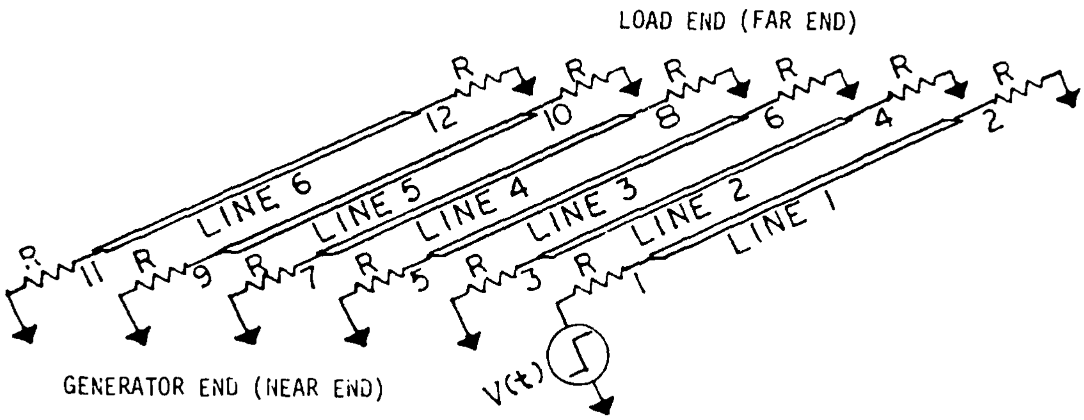
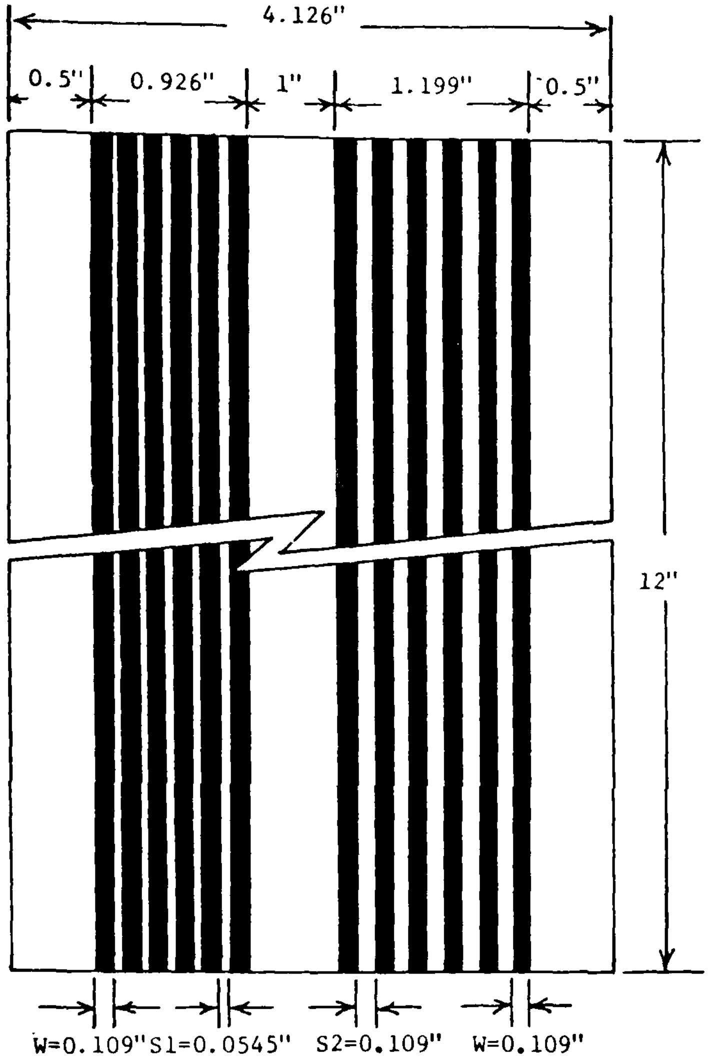


Figure 16. Circuit showing the applied voltage and the terminated transmission line.



ϵ_r = 4.7 RELATIVE DIELECTRIC CONSTANT (GLASS EPOXY)

t = 0.002" COPPER THICKNESS

h = 0.062" DIELECTRIC THICKNESS

W = 0.109" LINE WIDTH

S1 = 0.0545" SPACING (GROUP 1)

S2 = 0.109" SPACING (GROUP 2)

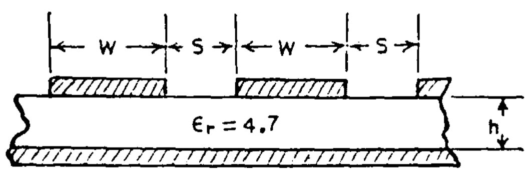
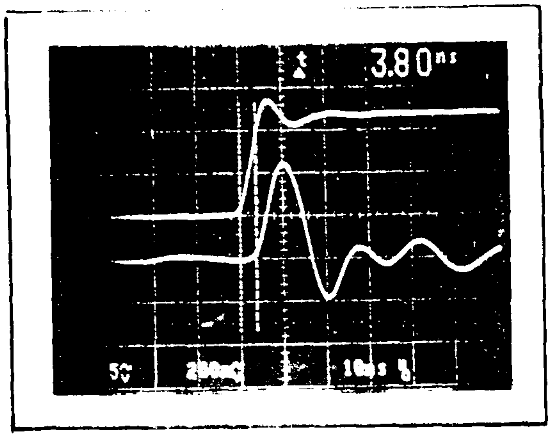


Figure 17. Sketch of the microstrip transmission line with six signal conductors for each group: group 1 and group 2.

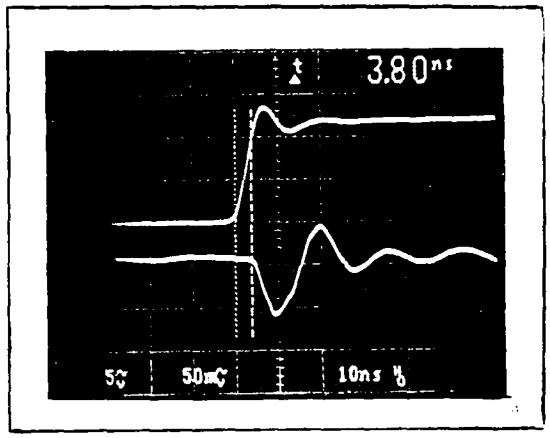
EXPERIMENTAL INVESTIGATION

CROSSTALK AS A FUNCTION OF LINE SPACING

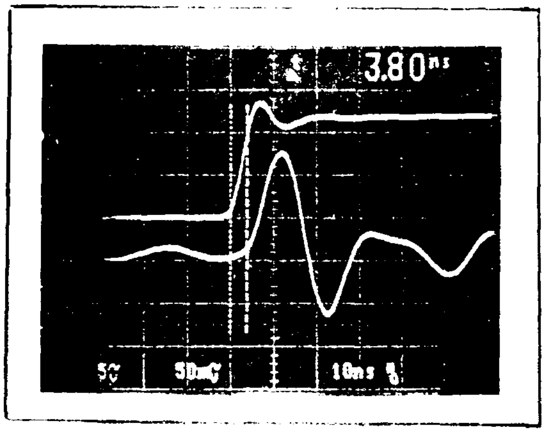
In this experiment, the dependence of crosstalk on line spacing was investigated. As previously mentioned, the degree of coupling was caused by the line geometry that controls the mutual capacitance and mutual inductance. The dependence of the forward and backward crosstalks to line spacing was determined by increasing the separation between the lines. Using equations 30 and 31 to predict the exact value of the crosstalk was not obtained at this time due to the relative magnitude of the rise time to electrical delay of the line. Further investigations of rise time effects were performed, and they are described in the section: "Crosstalk as a Function of Rise Time (2-Foot line)." The results for the two different groups are depicted in figure 18 and table 5. The experiment shows that the coupling and crosstalks between the lines decreases with increasing separation. This certainly is no surprise; the experimental result agrees with the equations 42 and 45 and figures 13 and 14.



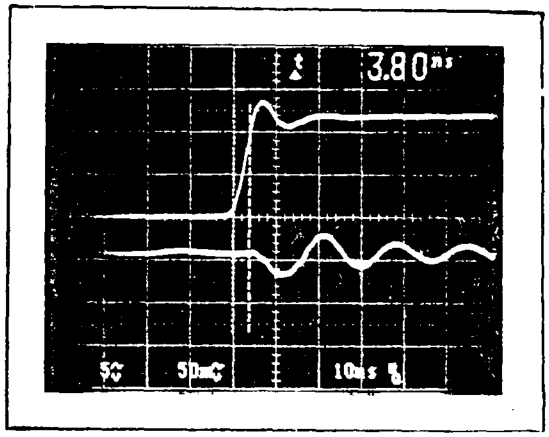
[illegible] and [illegible]



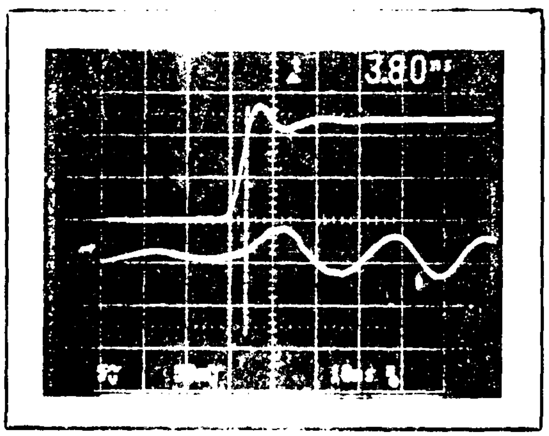
(b) Waveforms at [illegible]

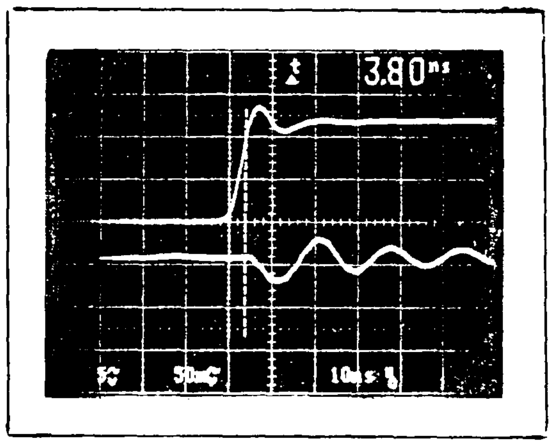


[illegible]



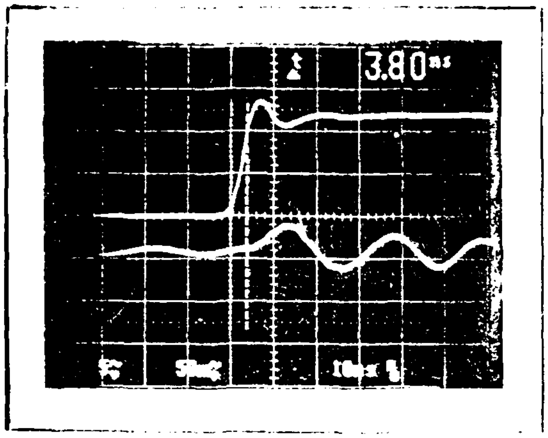
(d) Waveforms at [illegible]



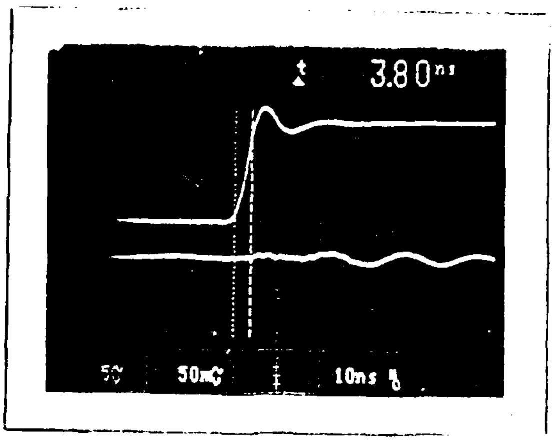


(f) [illegible]

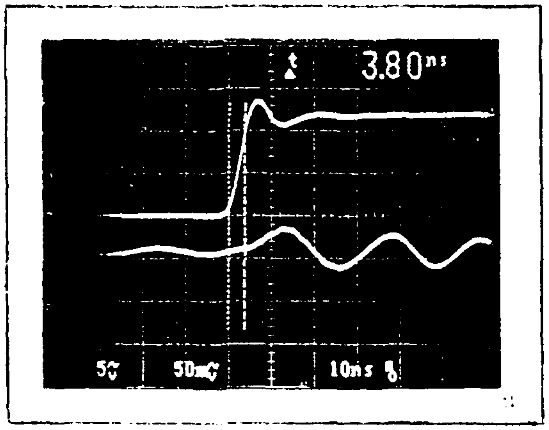
Figure [illegible] crosstalk waveforms of group 1. Line length = 1 foot. [illegible] rise time = 4.42 ns



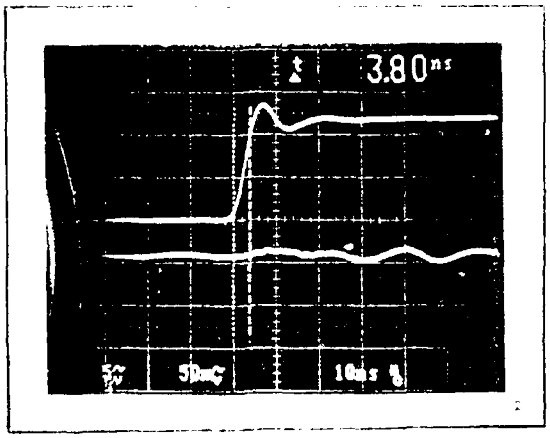
(g)Waveforms at terminals 1 and 9



(h)Waveforms at terminals 1 and 10

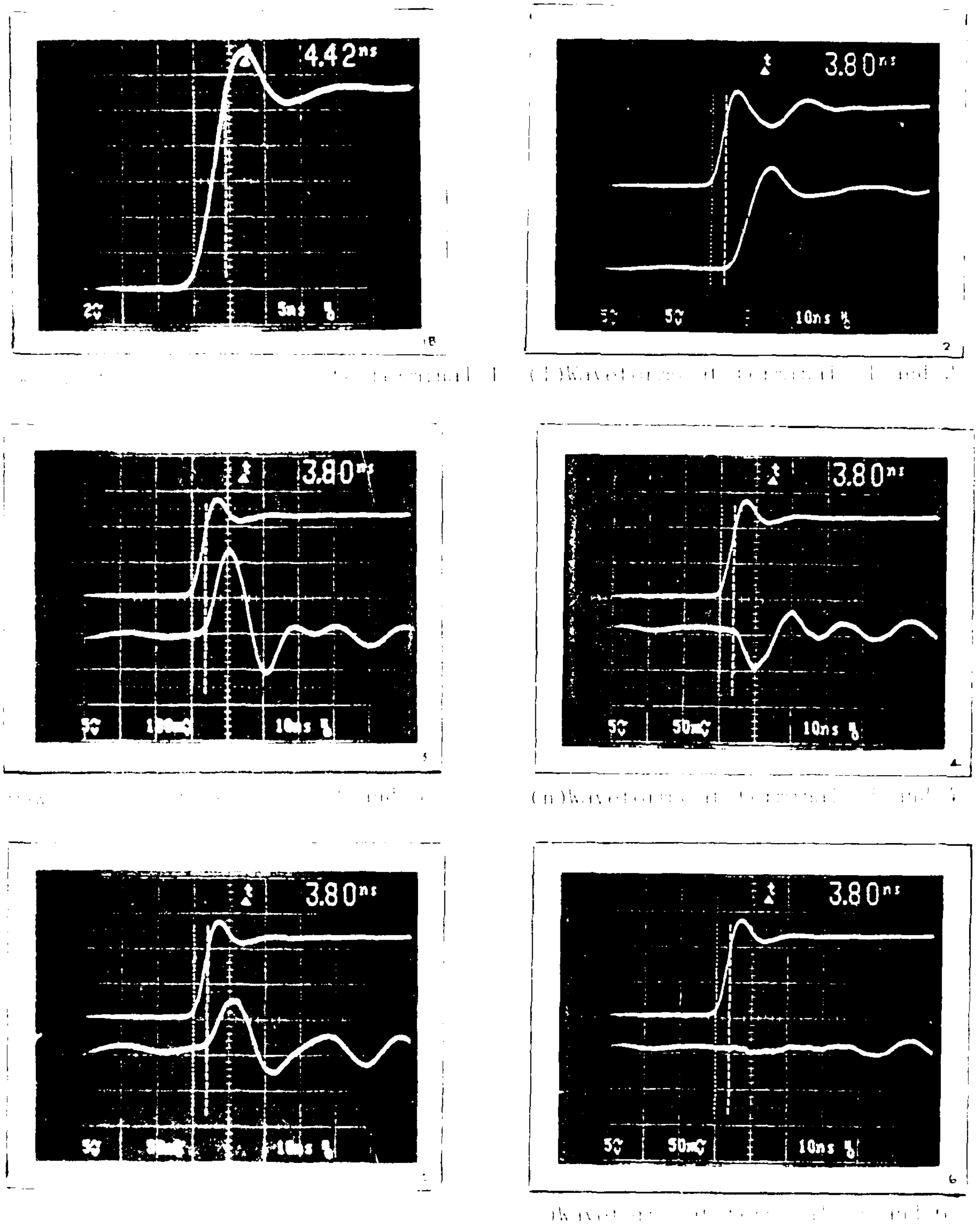


(i)Waveforms at terminals 1 and 11

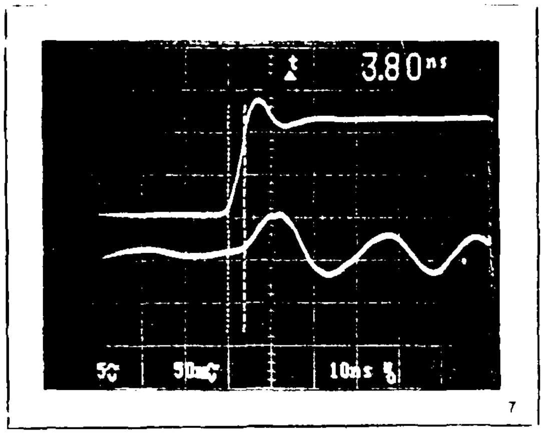


(j)Waveforms at terminals 1 and 12

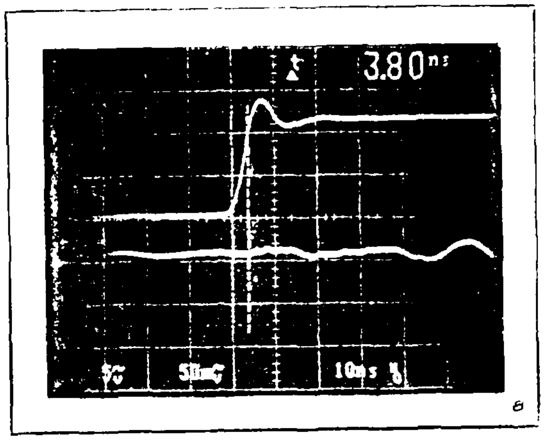
Figure 18 (cont) Observed crosstalk waveforms of group 1. Line length = 1 foot, line spacing = 54.5 mils, rise time = 4.42 ns.



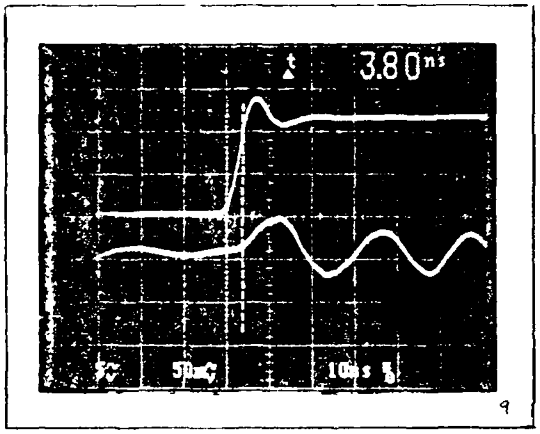
crosstalk waveforms of group 2 Line length 1 foot
time 4.42 ns



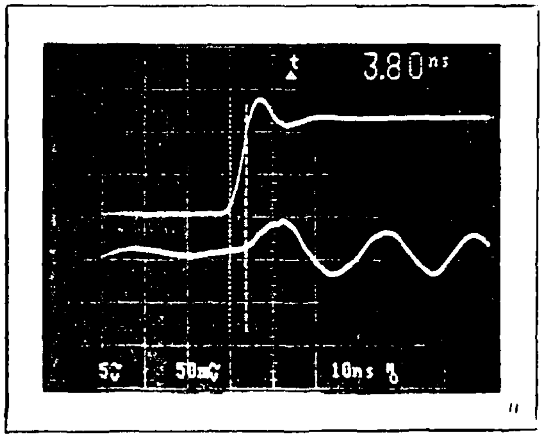
(q)Waveforms at terminals 1 and 7



(r)Waveforms at terminals 1 and 8



(s)Waveforms at terminals 1 and 9



(t)Waveforms at terminals 1 and 11

Figure 18 (cont). Observed crosstalk waveforms of group 2. Line length = 1 foot; line spacing = 109 mils; rise time = 4.42 ns.

Table 5. Comparison of group 1 and group 2 voltages.

Terminal Number*	Group 1 (mV)	Group 2** (mV)
1	11 Volts	11 Volts
2	11 Volts	11 Volts
3	440	225
4	-60	-45
5	120	75
6	-15	-10
7	40	30
8	-15	0
9	30	20
10	0	0
11	28	20
12	0	0

*The terminal numbers are indicated in figure 16. The observed crosstalk waveforms at the various terminals are shown in figure 18.

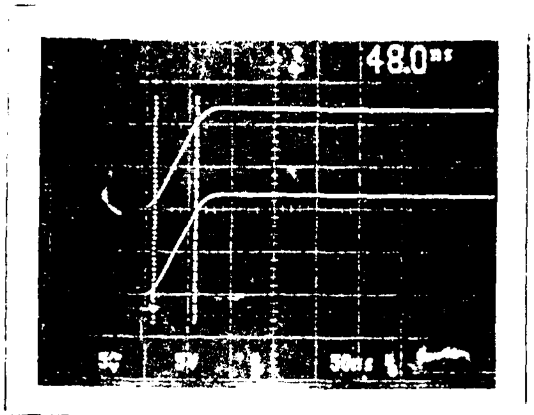
**Group 2 line spacing is twice that of group 1.

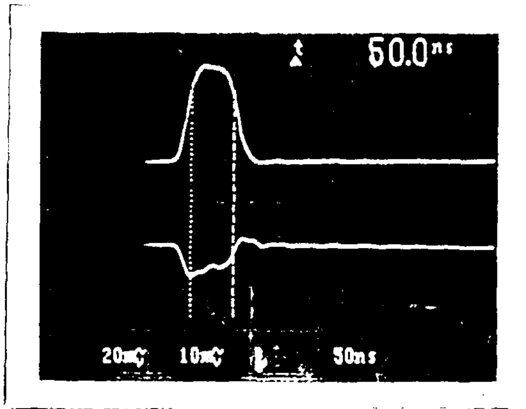
CROSSTALK AS A FUNCTION OF THE RISE TIME (1-FOOT LINE)

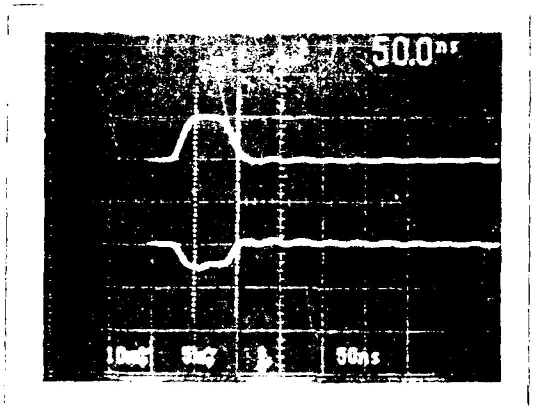
In this experiment, the dependence of crosstalk on the time differential of the applied signal was investigated. The signal rise time was increased from 4.4 ns to 48 ns resulting into a signal rise time that is much greater than the electrical delay of the line. A comparison of measured waveforms between a signal with a 4.4 ns rise time to a signal with 48 ns is shown in table 6. Figures 19 and 20 provide time domain data. Measurements were taken from a one-foot microstrip transmission line. The experiment shows that increasing the rise time of the input signal results into a corresponding decrease in crosstalk voltage. It is interesting to note that equations 42, 43, and 44 show this result via the dv/dt term. In these equations, increasing dt results into a corresponding decrease in forward crosstalk V_f.

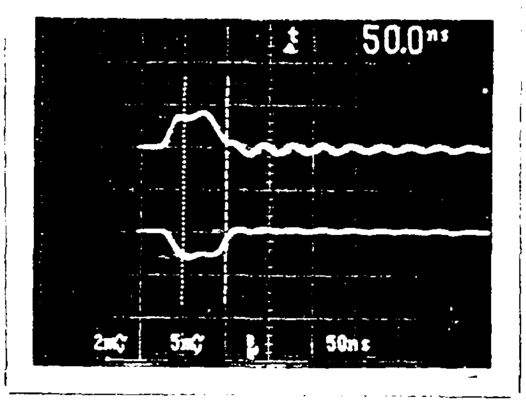
Table 6. Measured crosstalk waveforms showing crosstalk as a function of the rise time.

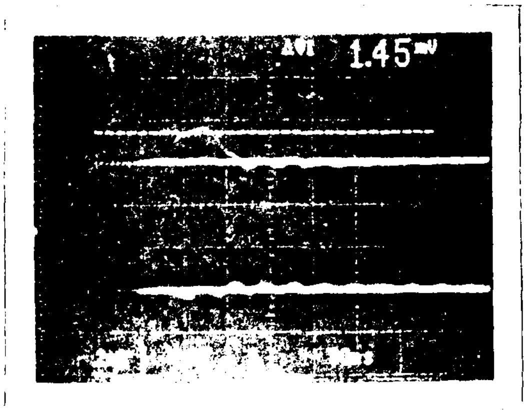
Terminal Number	4.4ns Signal (mV)	48 ns Signal (mV)
1	11 Volts	11 Volts
2	11 Volts	11 Volts
3	440	44
4	-60	-6.1
5	120	11
6	-15	-2.5
7	40	1.5
8	-15	-1.65
9	30	1.45
10	0	0
11	28	0.8
12	0	0

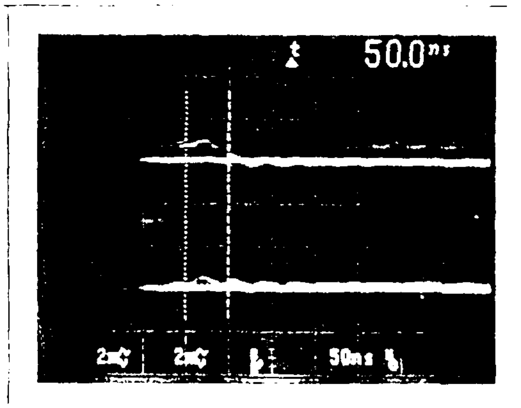




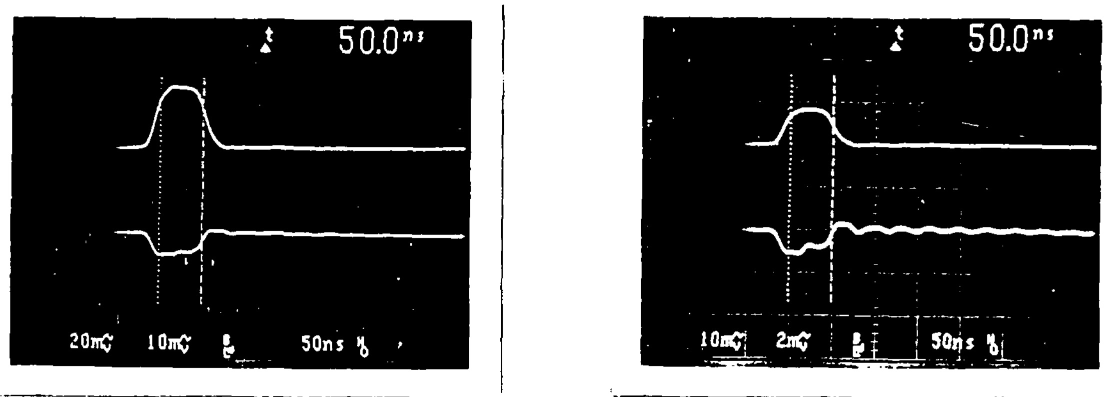








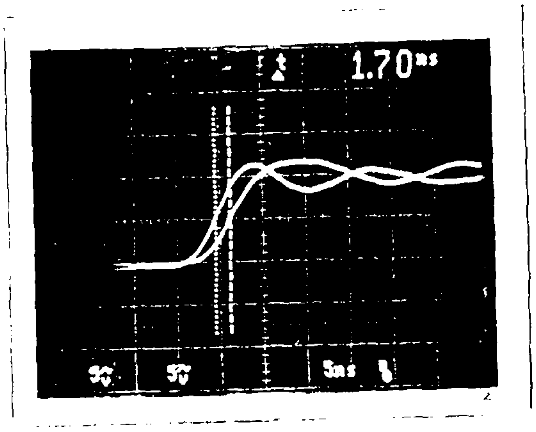
... crosstalk waveforms of group ... line length ...
... rise time 48 ns.



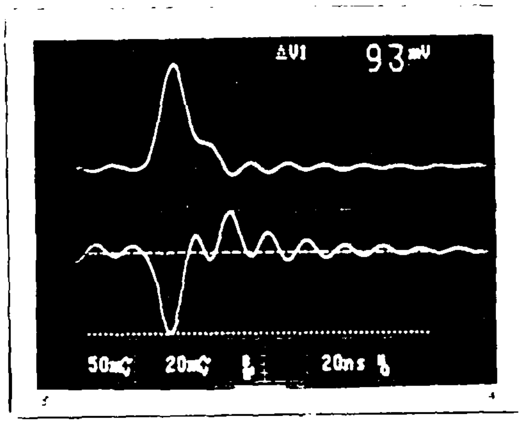
(g) Crosstalk waveforms at terminals 3 and 4

(h) Crosstalk waveforms at terminals 5 and 6

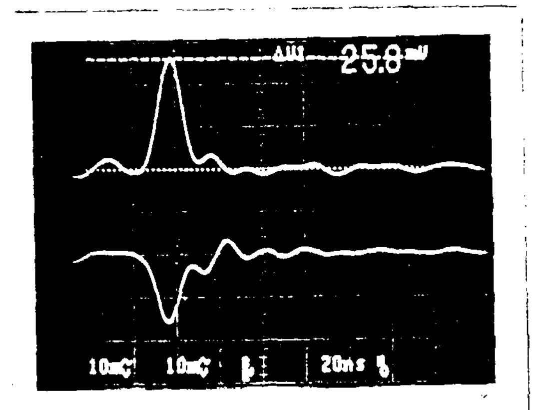
Figure 19 (cont). Observed crosstalk waveforms of group 2. Line length = 1 foot; line spacing = 109 mils; rise time = 48 ns.



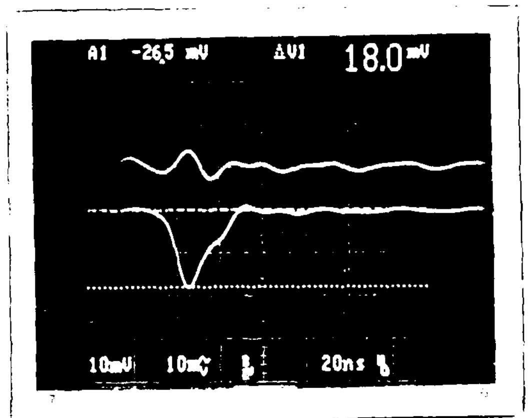
(a) [illegible] at Terminals



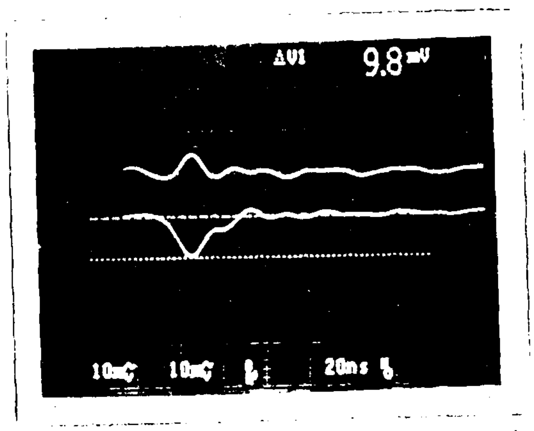
(b)Crosstalk Waveforms at Terminals
3 and 4



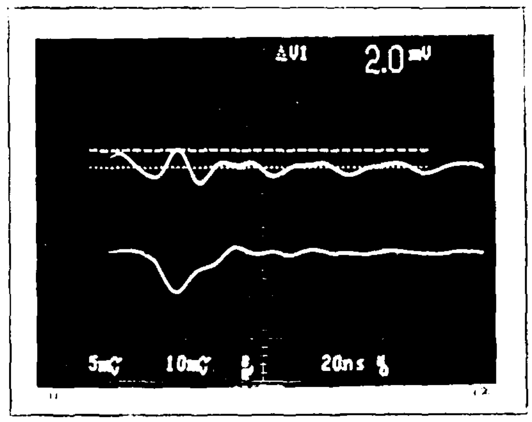
(c)Crosstalk Waveforms at Terminals



(d)Crosstalk Waveforms at Terminals
7 and 8

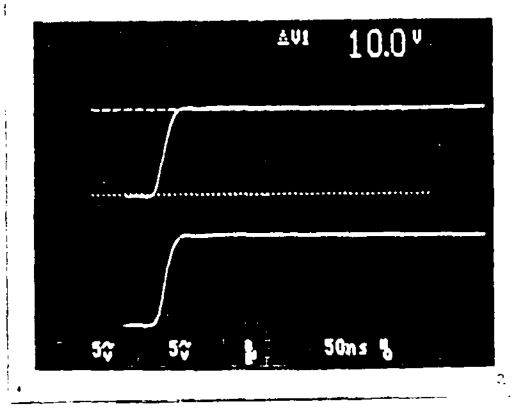


[illegible] Terminals

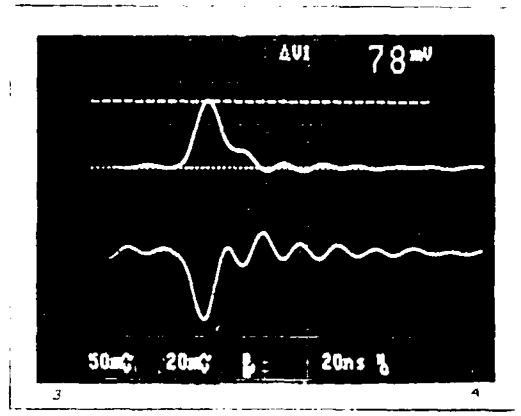


(f)Crosstalk Waveforms at Terminals
11 and 12

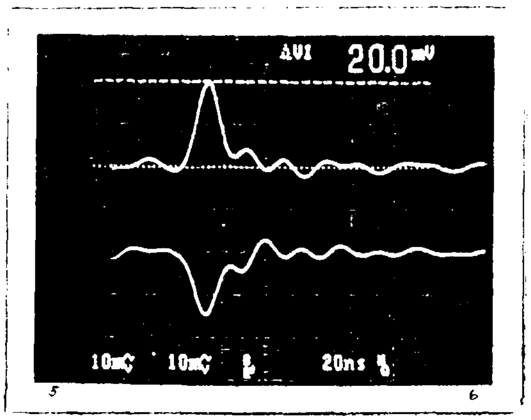
Figure 20 Observed crosstalk waveforms of group 1. Line length 1 foot
line spacing 54.5 mils; rise time 4.5 ns.



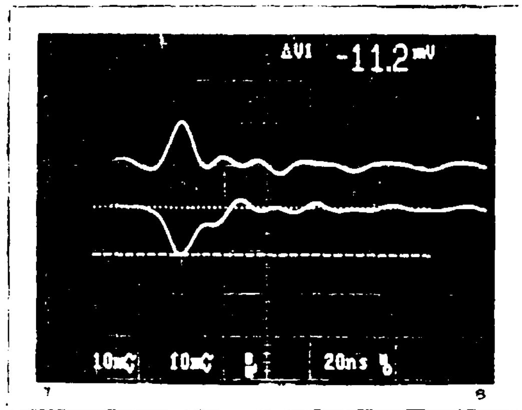
(g) [illegible] waveforms at Terminals 1 and 2



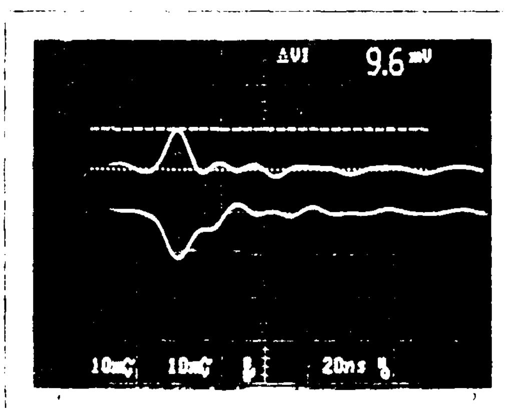
(h) Crosstalk waveforms at Terminals 3 and 4



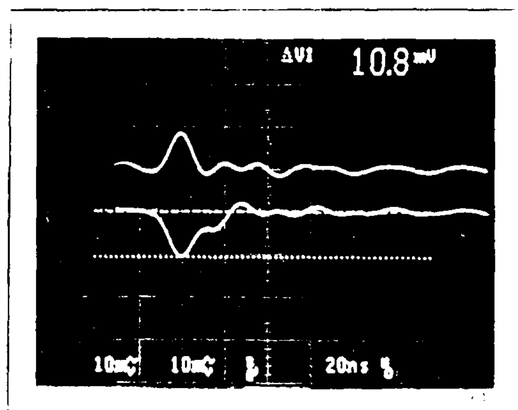
(i) Crosstalk Waveforms at Terminals 5 and 6



(j) Crosstalk Waveforms at Terminals 7 and 8



[illegible] Waveforms at Terminals [illegible]



(l) Crosstalk Waveforms at Terminals 11 and 12

Figure 20 (cont). Observed crosstalk waveforms of group 2. Line length = 1 foot, line spacing = 109 mils, rise time = 4.5 ns.

VERIFICATION OF THE PROPAGATION TIME DELAY T_D

As previously described, the propagation delay of the microstrip transmission line is dependent only on the dielectric constant of the printed circuit board. Using equation 24, the propagation delay is calculated as

$$T_D = 1.017\sqrt{0.475\,\epsilon_r + 0.67}\ \text{ns/ft}$$

$$= 1.017\sqrt{0.475(4.7) + 0.67}$$

$$T_D = 1.72\ \text{ns/ft}\ .$$

Experimental data coincides with the calculated value of the propagation time delay T_D. The computed propagation time delay of 1.72 ns/ft closely agrees with the measured time of 1.70 ns between terminals 1 and 2 of conductor 1 (figure 20a).

VERIFICATION OF THE POLARITIES OF THE BACKWARD AND FORWARD WAVES

As expressed by equations 39 and 41 for the forward and backward waves, the experimental results (compare all photographed figures) show that the backward wave has the same positive-going form as the input signal. This positive-going wave on the active line (line 1) also produces a negative voltage, the forward wave, on the adjacent lines. (figure 16).

In this experiment, the 20-MHz BW Limit Button in the scope was activated. This limits the bandwidth of the vertical deflection system to 20 MHz, thus providing a smoother and distinct display of the waveform; however, the net effect of this method is an overall reduction in the peak-to-peak voltage display. It reduces the amplitude of the waveform to about 30 to 40 percent.

CROSSTALK PREDICTION IN A 2-FOOT MICROSTRIP TRANSMISSION LINE

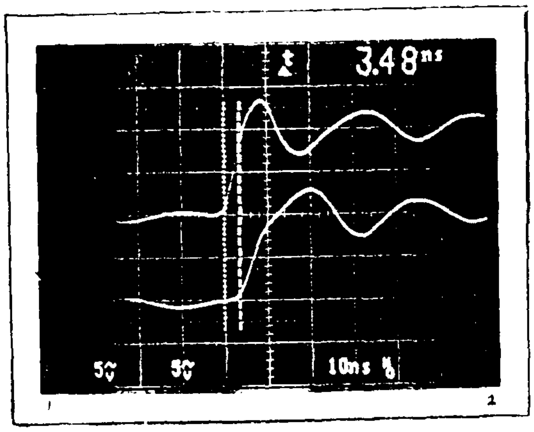
In this experiment, the length of the microstrip transmission line was increased from one foot to two feet. The rise time of the applied voltage tr was 4.5×10^{-9} sec. The effect of the increased length is an overall increase in the electrical delay of the line, resulting in a signal rise time that is less than twice the electrical delay of the line. This is verified by calculating the values of $2\ell/u$

$$\mu = \frac{1}{T_D} = \frac{1}{1.73 \times 10^{-9}\ \text{sec/ft}} = 5.77 \times 10^{8}\ \text{ft/sec}$$

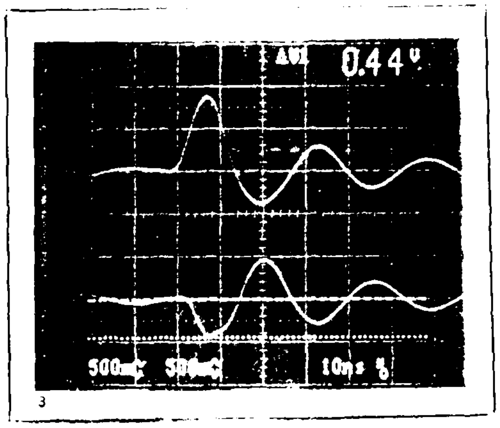
$$\frac{2\ell}{\mu} = \frac{2(2\ \text{ft})}{5.71 \times 10^{8}\ \text{ft/sec}} = 5.93 \times 10^{-9}\ \text{sec}\ .$$

Since the rise time tr = 4.5×10^{-9} sec, it satisfies the requirement that tr $< 2\ /\mu$, i.e., $4.5 < 5.93$ ns.

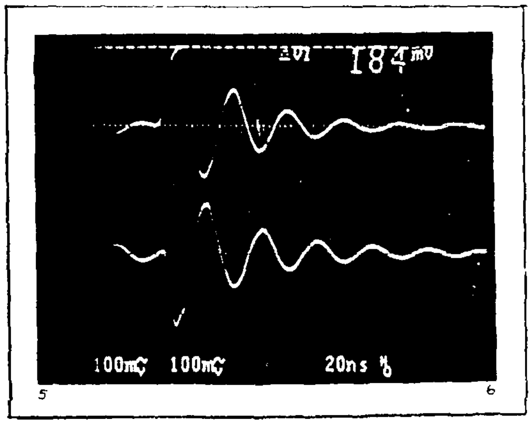
Figure 21 shows the observed crosstalk waveforms of group 1 and group 2. The predicted amplitude response of the adjacent conductor was calculated (see appendix c1) by taking the corresponding values of the backward and forward crosstalk constants from figures 13 and 14 and substituting into equations 30 and 31. Table 7 shows the comparison



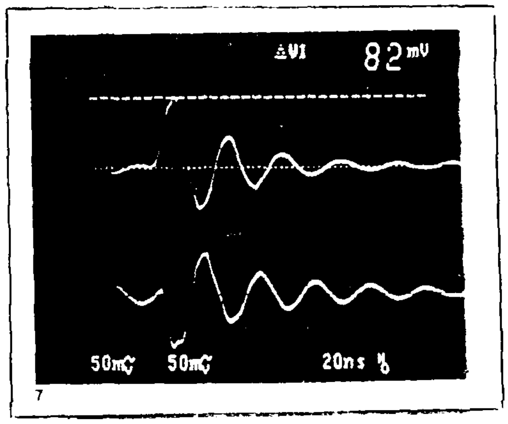
(a)Signal Waveforms at Terminals 1 and 2



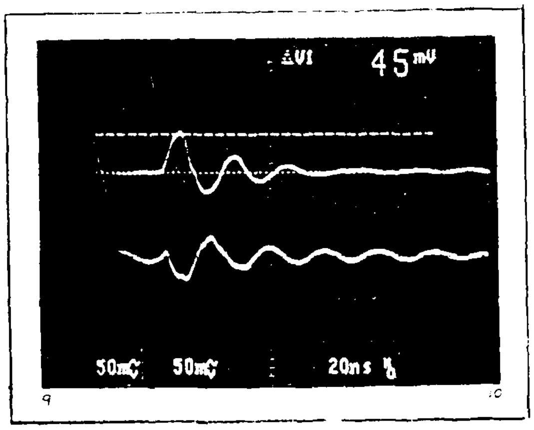
(b)Crosstalk Waveforms at Terminals 3 and 4



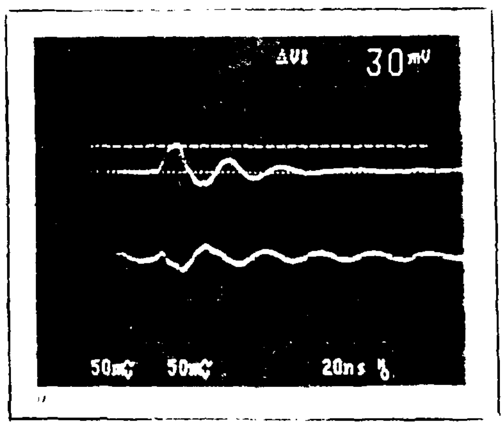
(c)Crosstalk Waveforms at Terminals 5 and 6



(d)Crosstalk Waveforms at Terminals 7 and 8

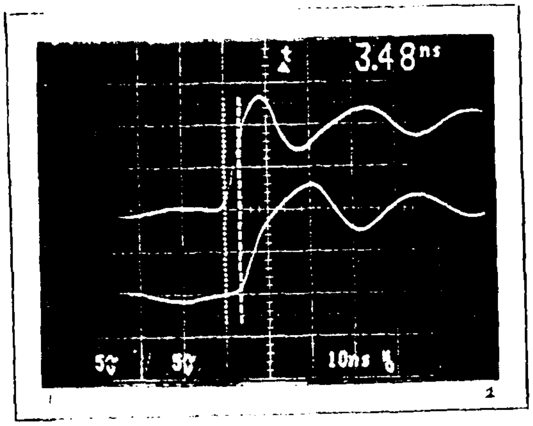


(e)Crosstalk Waveforms at Terminals 9 and 10

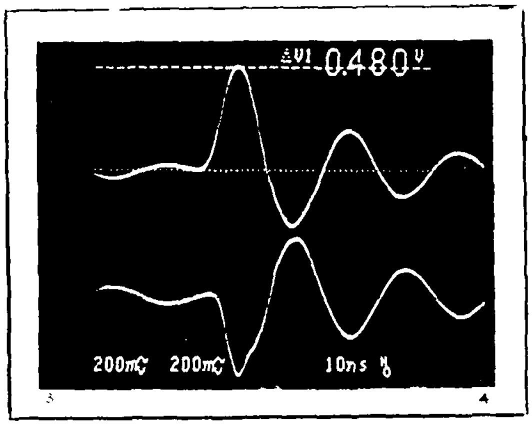


(f)Crosstalk Waveforms at Terminals [illegible]

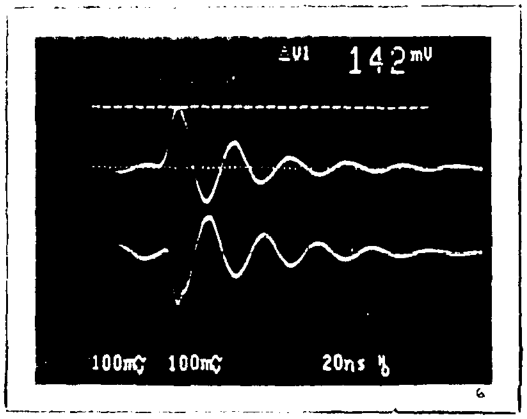
Figure 21. Observed crosstalk waveforms of group 1 [illegible] feet, line spacing = 54.5 mils, rise time = 4.5 ns.



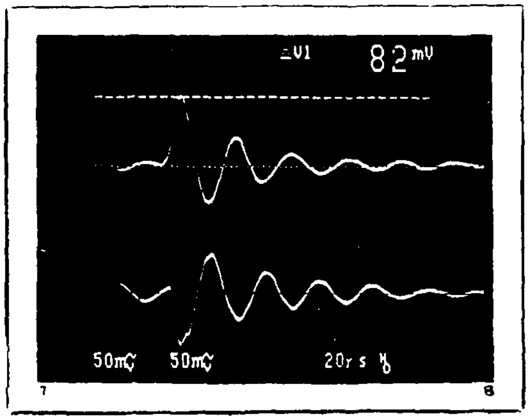
(a) ... at Terminals ... 2



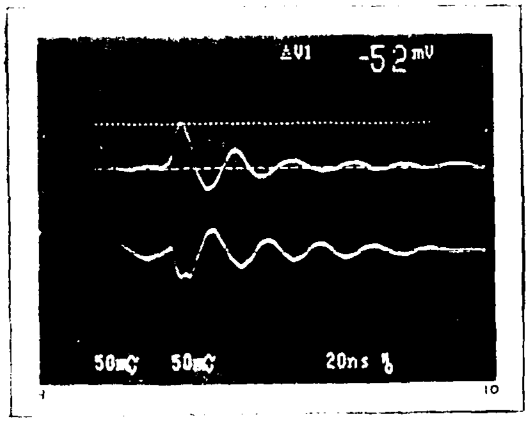
(b)Crosstalk Waveforms at Terminals 3 and 4



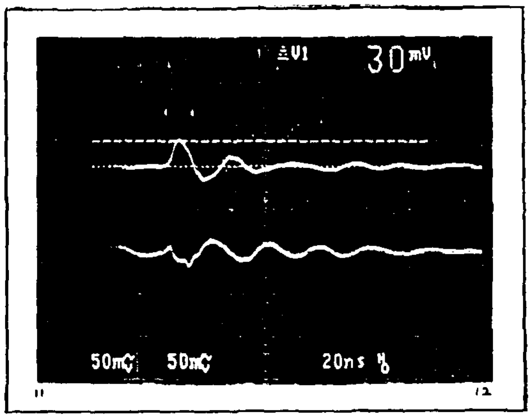
(c)Cross... at Terminals



(d)Crosstalk Waveforms at Terminals 7 and 8

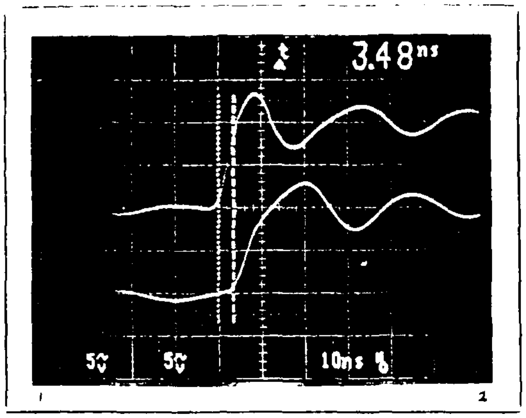


(e)... Terminals

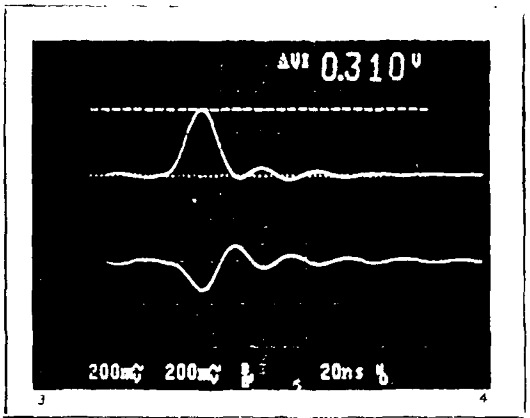


(f)Crosstalk Waveforms at Terminals 11 and 12

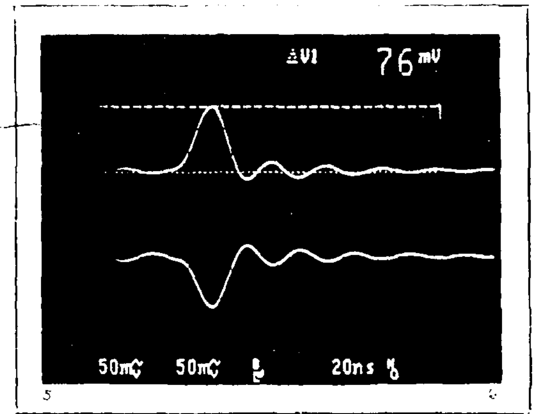
Figure 21 (cont) Observed crosstalk waveforms of group 2. Line length = 2 feet; ... rise time = 4.5 ns.



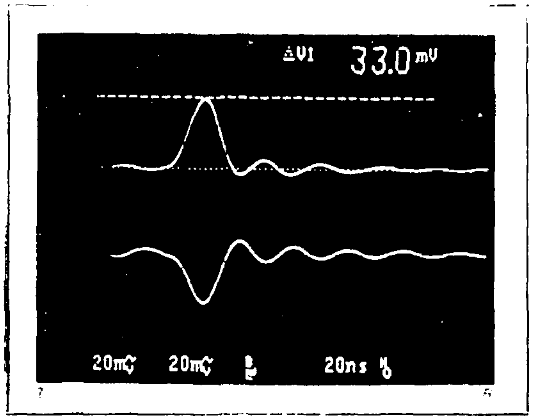
(a)Signal Waveforms at Terminals 1 and 2



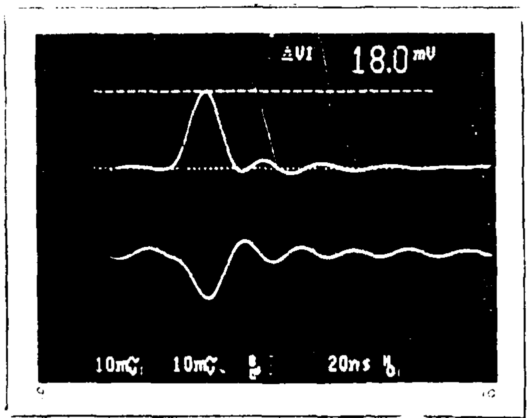
(b)Crosstalk Waveforms at Terminals 3 and 4



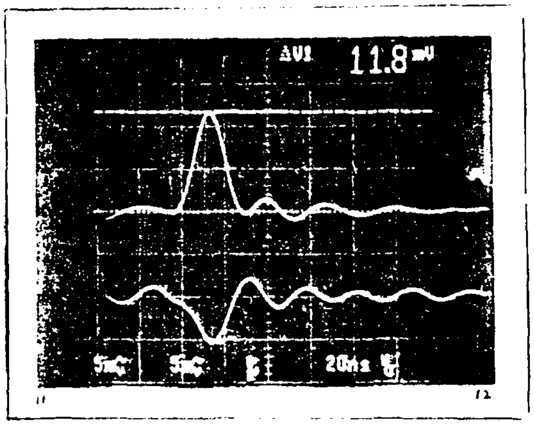
(c)Crosstalk Waveforms at Terminals 5 and 6



(d)Crosstalk Waveforms at Terminals 7 and 8

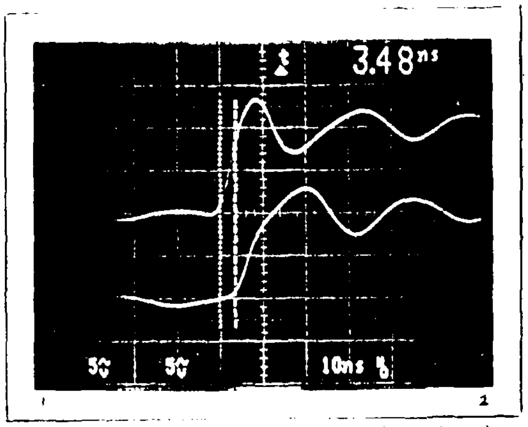


(e)Crosstalk Waveforms at Terminals 9 and 10

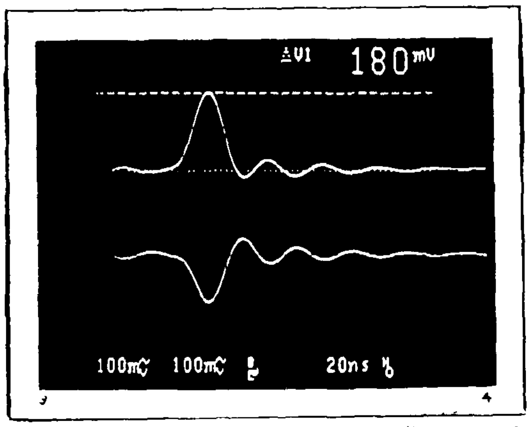


(f)Crosstalk Waveforms at Terminals 11 and 12

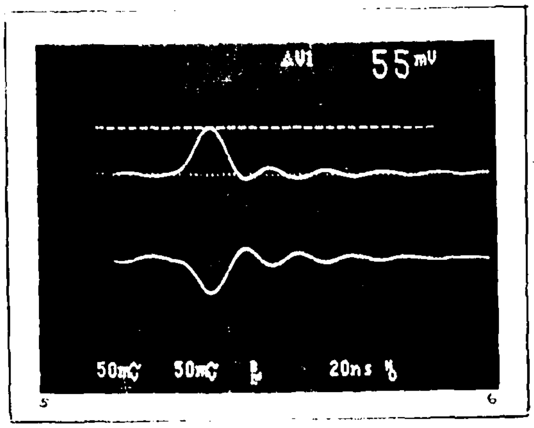
Figure 21 (cont). Observed crosstalk waveforms of group 1 with the 20 MHz BW limit activated in the scope. Line length = 2 feet, line spacing = 54.5 mils; rise time = [illegible]



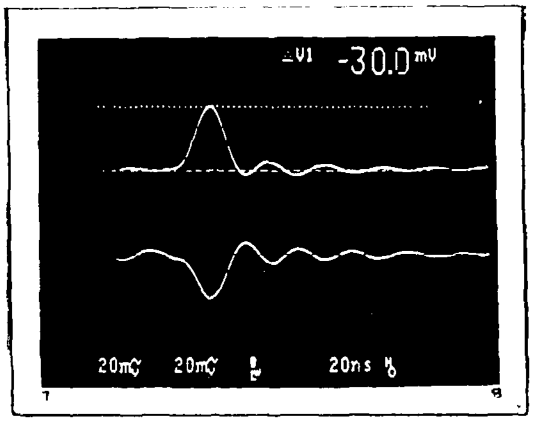
(a)Signal Waveforms at Terminals
1 and 2



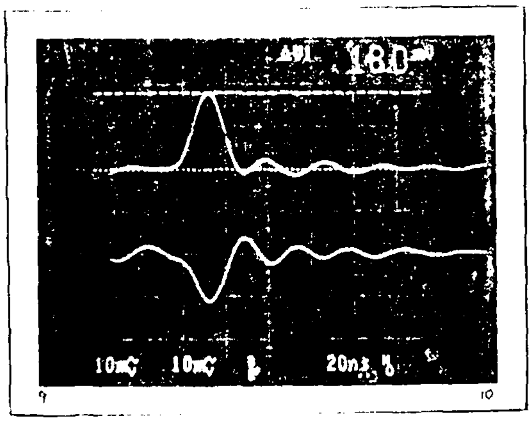
(b)Crosstalk Waveforms at Terminals
3 and 4



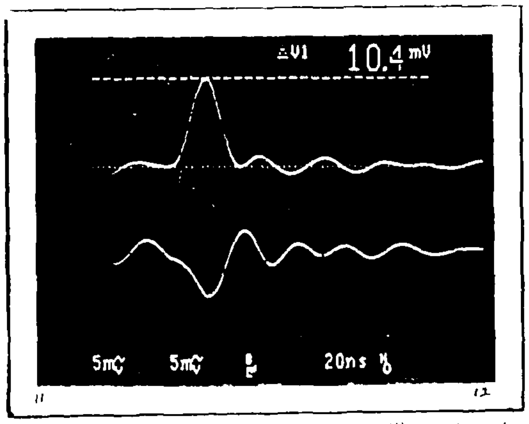
(c)Crosstalk Waveforms at Terminals
5 and 6



(d)Crosstalk Waveforms at Terminals
7 and 8



(e)Crosstalk Waveforms at Terminals
9 and 10



(f)Crosstalk Waveforms at Terminals
11 and 12

Figure 21 (cont). Observed crosstalk waveforms of group 2 with the 20-MHz BW limit activated [illegible] 2 feet, line spacing = 109 mils; rise time 4.5 ns.

Table 7. Comparison of predicted amplitude to measured amplitude of the backward and forward crosstalks.

Group 1

V = 10 Volts *	Calculated(Volts)	Measured(Volts)
Forward Crosstalk (Terminal 4)	-0.43	-0.44
Backward Crosstalk (Terminal 3)	1.2	0.84

Group 2

V = 10 Volts *	Calculated(Volts)	Measured(Volts)
Forward Crosstalk (Terminal 4)	-0.324	-0.34
Backward Crosstalk (Terminal 3)	0.50	0.48

*V = 10 volts, input voltages

between the predicted value and the measured value of the forward and backward crosstalk. With the exception of the measured value at terminal 3, the computed amplitude of the backward crosstalk at the generator end (near end) and the amplitude of the forward crosstalk at the load end (far end) closely agree with the experimental results. The disparity between the measured value and calculated value at terminal 3 was believed to have been caused by the location of the scope ground probe during the measurement. That is, as the ground probe connection was relocated some change was observed in measured value, an estimated 30 percent error was introduced by relocating the ground probe.

CROSSTALK AS A FUNCTION OF THE INPUT SIGNAL

This experiment demonstrates that the magnitude of the crosstalk induced into the nearby conductors of a microstrip transmission line is a function of the magnitude of the input signal.

Various levels of voltages were applied into terminal 1 of the microstrip transmission line. Corresponding level of crosstalk voltages were measured from the generator end and the load end of the transmission line. The measured voltages were tabulated in table 8. The effects of these varying applied voltages to the nearby conductor were predicted by calculating (see appendix C2) the level of crosstalk at terminals 3 and 4. Table 9 shows the predicted and measured values of crosstalk.

Table 8. Measured crosstalk values showing crosstalk as a function of the input signal.

	Input Voltage V = 10.5 volts		Input Voltage V = 7 volts		Input Voltage V = 3.5 volts	
Terminal Number	Group 1 (mV)	Group 2 (mV)	Group 1 (mV)	Group 2 (mV)	Group 1 (mV)	Group 2 (mV)
1	10.5 V	10.5 V	7 V	7 V	3.5 V	3.5 V
2	10.5 V	10.5 V	7 V	7 V	3.5 V	3.5 V
3	680	380	455	265	215	126
4	-340	-275	-225	-185	-110	-100
5	146	110	96	78	47	37
6	-118	-96	-80	-66	-47	-37
7	64	62	43	43	20.5	20
8	-45	-45	-31	-26	-19	-16
9	36	36	24	26	13	13
10	-20	-24	-12.5	-12	-10	-8
11	24	21	16	16	8.5	6.8
12	-10	-10	-4.5	-4	-4.5	-4

Table 9. Comparison of predicted and measured values of the forward and backward crosstalks.

V = 10.5 Volts	Group 1		Group 2	
	Calculated (Volts)	Measured (Volts)	Calculated (Volts)	Measured (Volts)
Forward Crosstalk (Terminal 4)	-0.322	-0.34	-0.243	-0.27
Backward Crosstalk (Terminal 3)	0.96	0.68	0.378	0.38

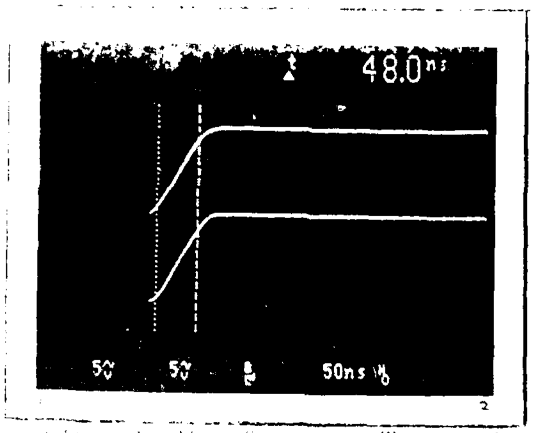
V = 7 Volts	Group 1		Group 2	
	Calculated (Volts)	Measured (Volts)	Calculated (Volts)	Measured (Volts)
Forward Crosstalk (Terminal 4)	-0.214	-0.225	-0.162	-0.18
Backward Crosstalk (Terminal 3)	0.644	0.5	0.25	0.26

V = 3.5 Volts	Group 1		Group 2	
	Calculated (Volts)	Measured (Volts)	Calculated (Volts)	Measured (Volts)
Forward Crosstalk (Terminal 4)	-0.11	-0.11	-0.08	-0.10
Backward Crosstalk (Terminal 3)	0.322	0.22	0.126	0.126

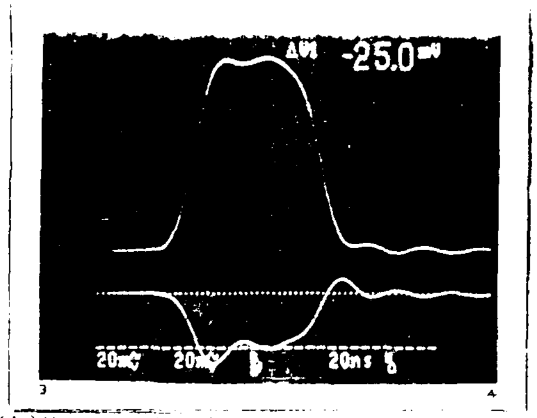
The result of the experiment shows that decreasing the input signal into the system causes a corresponding decrease of crosstalk in the system. This is the property of the linear system. The output amplitude is proportional to the input amplitude. Equations 39 and 41 have predicted this result via the $V/2$ and dV/dt terms.

CROSSTALK AS A FUNCTION OF THE RISE TIME (2-FOOT LINE)

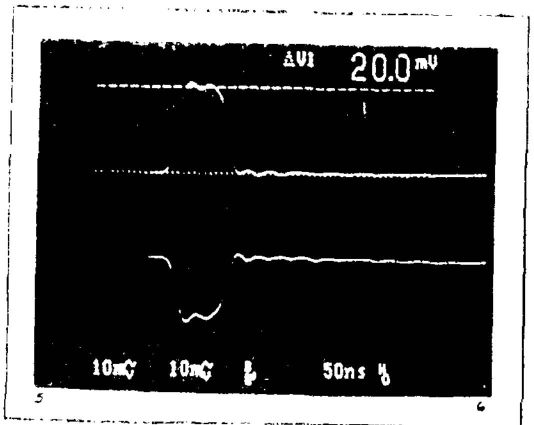
In this experiment, the effect of the varying rise time to crosstalk was revisited (see prior discussion in crosstalk as a function of rise time (1-foot line)), using a 2-foot microstrip transmission line. This is done to verify that a longer microstrip line will show the same result as that of the shorter one. Figures 22 and 23 show the magnitude of the waveforms measured from the various terminals of the generator end (near end) and load end (far end) of the transmission line. Table 10 shows the relative comparison of the crosstalks that were generated from the input signals containing 4.5, 48, and 500 ns rise time. The experiment verifies that increasing the rise time of the input signal decreases the magnitude of the crosstalk voltage. Table 11 shows the comparison of predicted and measured values of the forward and backward crosstalks.



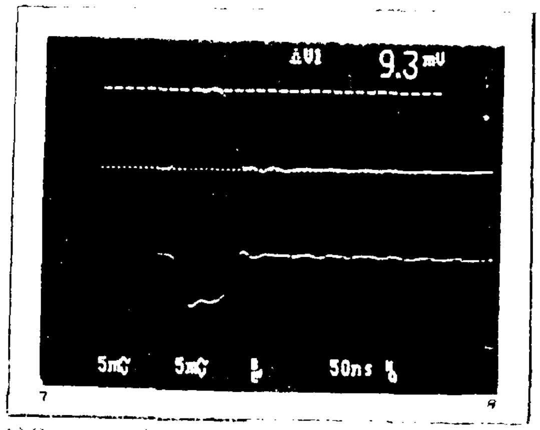
(a) [illegible] Waveforms at Terminals 1 and 2



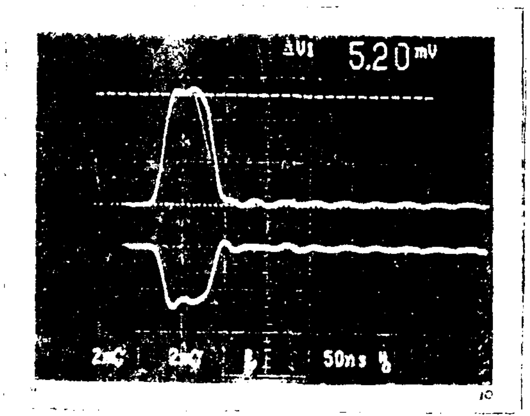
(b) Crosstalk [illegible] at [illegible]



[illegible] Crosstalk Waveforms at Terminals [illegible]



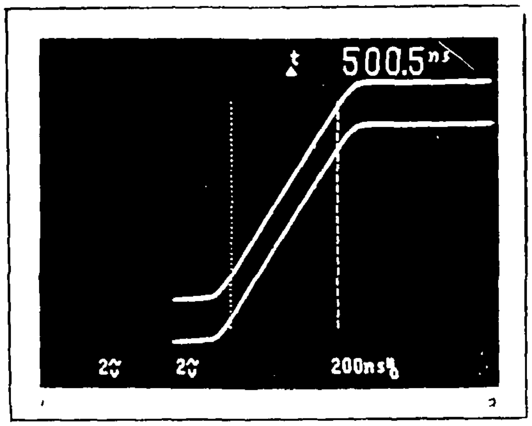
(d) Crosstalk [illegible] Terminals [illegible]



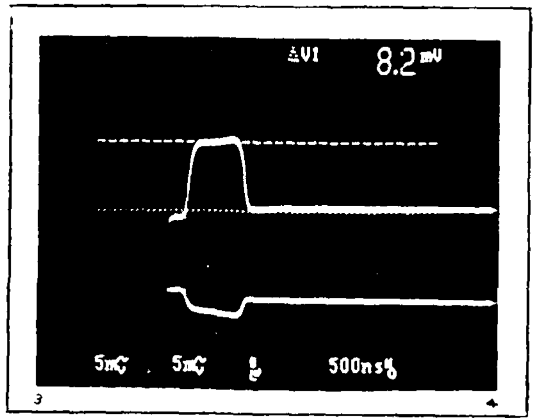
[illegible] Terminals [illegible] 10

(f) [illegible]

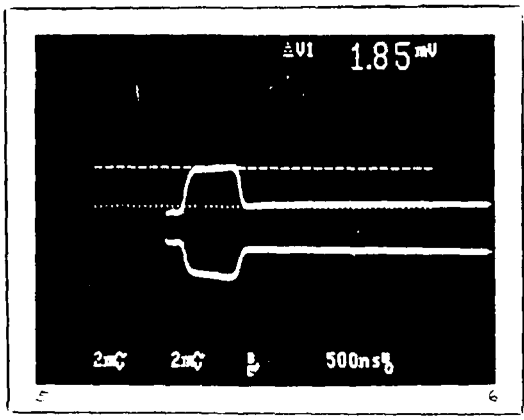
Figure 22. [illegible] crosstalk waveforms of group 1. Line length [illegible] line [illegible] mils [illegible] 48 ns



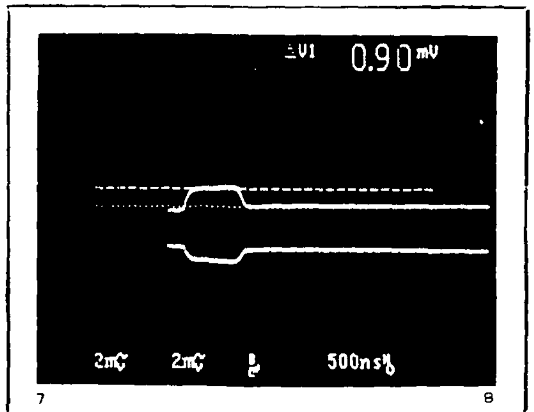
(a)Signal Waveforms at Terminals 1 and 2



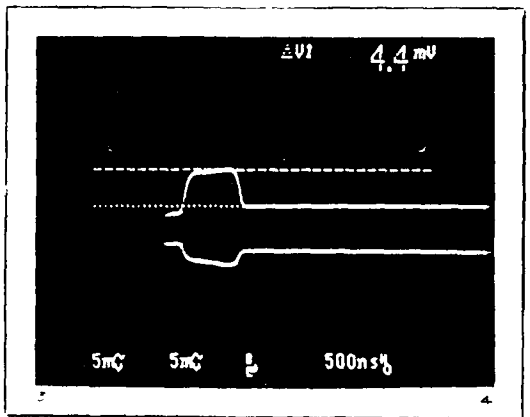
(b)Crosstalk Waveforms at Terminals 3 and 4



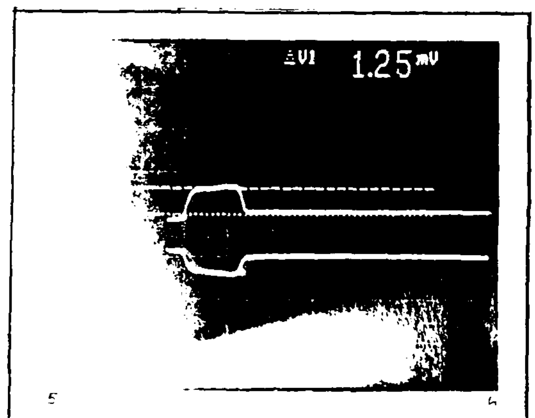
(c)Crosstalk Waveforms at Terminals 5 and 6



(d)Crosstalk Waveforms at Terminals 7 and 8



(e)Crosstalk Waveforms at Terminals 3 and 4



(f)Crosstalk Waveforms at Terminals 5 and 6

Figure 23. (a through d). Observed crosstalk waveforms of group 1. Line length = 2 feet; line spacing = 54.5 mils; rise time = 500 ns.

Figure 23 (cont). (e and f). Observed crosstalk waveforms of group 2. Line length = 2 feet; line spacing = 109 mils; rise time = 500 ns.

Table 10. Measured crosstalk waveforms showing crosstalk as a function of the rise time. Measurements were taken from a 2-foot microstrip transmission line.

Terminal Number	Rise Time 4.5 ns (mV)	Rise Time 48 ns (mV)	Rise Time 500 ns (mV)
1	10 Volts	10 Volts	10 Volts
2	10 Volts	10 Volts	10 Volts
3	840	100	8.2
4	-440	-25	-2.6
5	184	20	1.85
6	-164	-14	-1.25
7	82	9.3	0.9
8	-56	-5.5	-0.55
9	46	5.2	0.45
10	-25	-2.65	-0.35
11	30	3.35	0.35
12	-15	-1.1	-0.25

Table 11. Comparison of predicted and measured values of the forward and backward crosstalks.

Rise Time (4.5ns)	Group 1		Group 2	
V = 10 Volts	Calculated (Volts)	Measured (Volts)	Calculated (Volts)	Measured (Volts)
Forward Crosstalk (Terminal 4)	-0.43	-0.44	-0.324	-0.34
Forward Crosstalk (Terminal 3)	1.2	0.84	0.50	0.48

Rise Time (48ns)	Group 1		Group 2	
V = 10 Volts	Calculated (mV)	Measured (mV)	Calculated (mV)	Measured (mV)
Forward Crosstalk (Terminal 4)	-28	-25	-22	-22.5
Backward Crosstalk (Terminal 3)	130	100	52	52

Rise Time (500ns)	Group 1		Group 2	
V = 10 Volts	Calculated (mV)	Measured (mV)	Calculated (mV)	Measured (mV)
Forward Crosstalk (Terminal 4)	-2.8	-2.6	-1.3	-2.0
Backward Crosstalk (Terminal 3)	12	8.2	5	4.6

CROSSTALK SYMMETRICAL RESPONSE

The purpose of this experiment was just to verify the author's insight that a crosstalk symmetrical response does exist in the evenly spaced uniform conductors. No equations or proof were derived to predict this symmetrical response.

In this experiment, the effect of the input signal propagating along the conductor placed between the evenly spaced uniform conductors was investigated. In figure 24, power is applied to terminal 7 of line 4. The rise time of the input signal is 4.5 ns. The microstrip line is 2 feet in length and each conductor is terminated with a 50 ohms resistor. Various levels of crosstalk voltages were measured from each terminal and are shown in the figure. The result of the experiment shows that the induced crosstalk is symmetrical around the power line, i.e., line 4 in the figure.

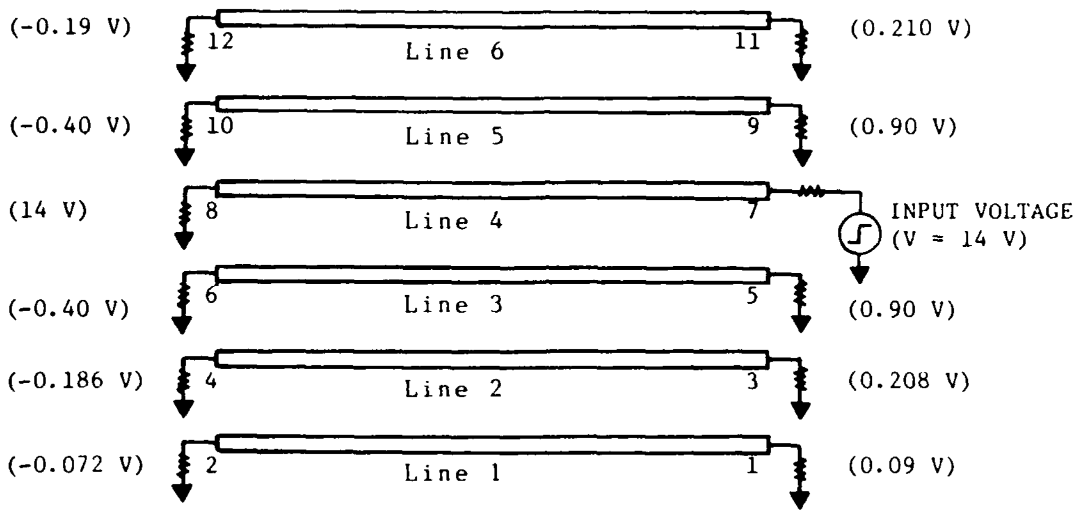
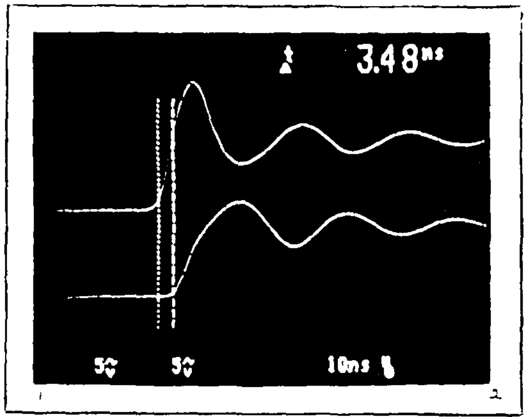


Figure 24. Sketch showing the symmetrical response of the crosstalk waveform around the power line.

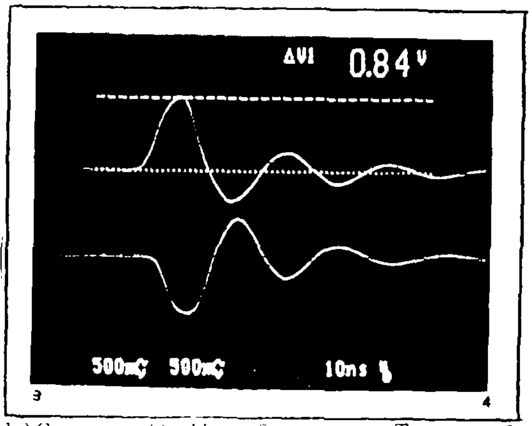
CROSSTALK AS A FUNCTION OF TERMINATIONS

The purpose of this experiment is to verify the previous theoretical discussion. No theoretical calculations were made to predict the effect of terminations; however, an experiment was conducted to illustrate this effect.

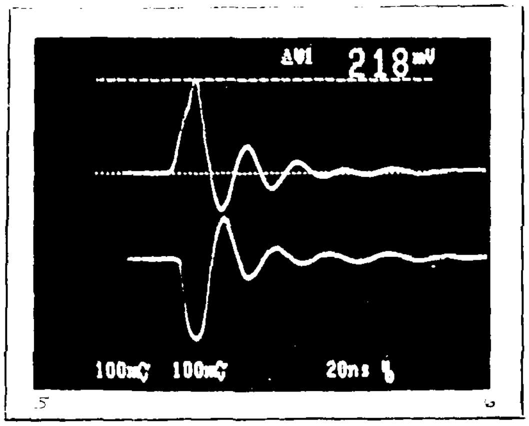
In this experiment, the effect of termination to crosstalk was investigated. To illustrate the effect, the circuit was configured in the following manner: in the first experiment, the transmission line was terminated with 27 ohm resistors. In the second experiment, the transmission line was short circuited at the far end. In the last series of this experiment, the transmission line was open circuited at the far end. The results of the experiment are shown in figures 25, 26 and 27 and tabulated in table 12.



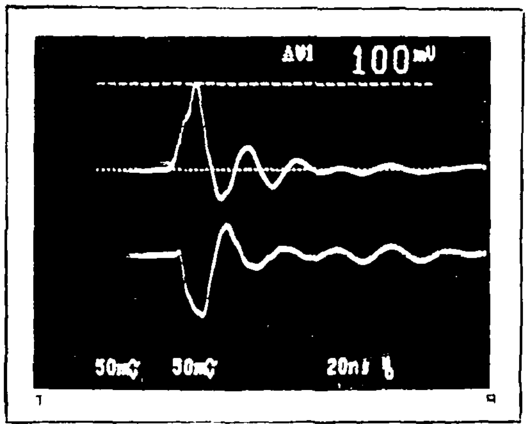
(a)Signal Waveforms at Terminals
1 and 2



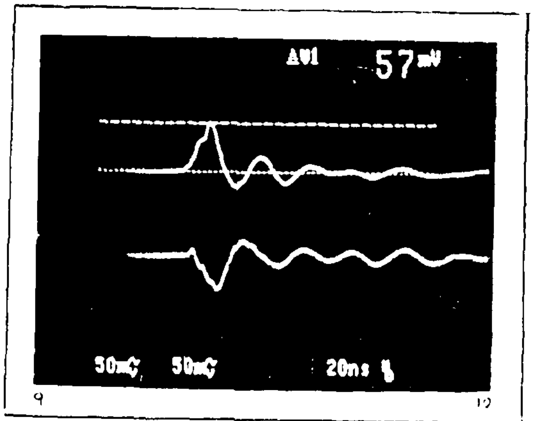
(b)Crosstalk Waveforms at Terminals
3 and 4



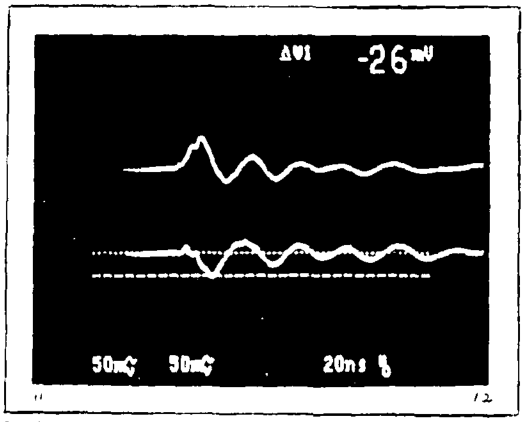
(c)Crosstalk Waveforms at Terminals
5 and 6



(d)Crosstalk Waveforms at Terminals
7 and 8

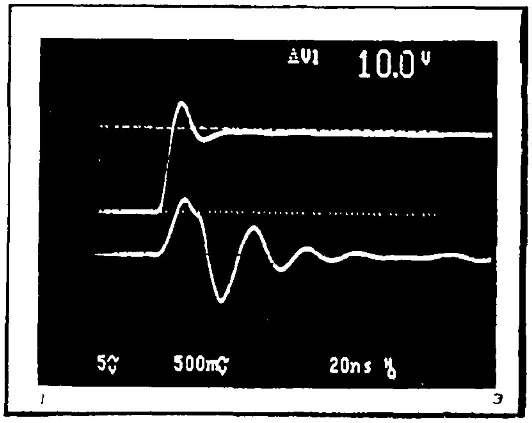


(e)Crosstalk Waveforms at Terminals
9 and 10

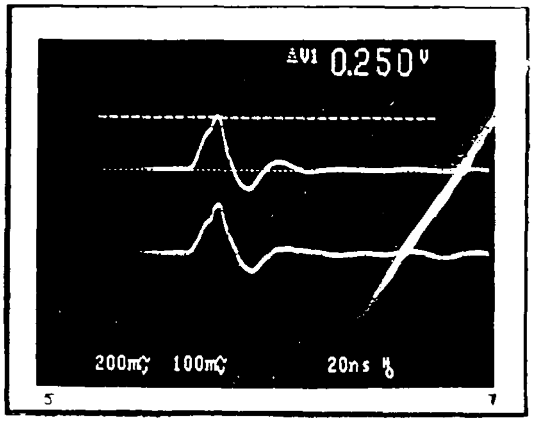


(f)Crosstalk Waveforms at Terminals
11 and 12

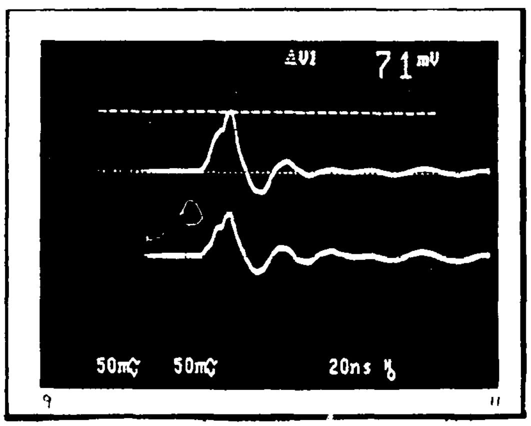
Figure 25. Observed crosstalk waveforms of group 1. Line length = 2 feet; line spacing = 54.5 mils; rise time = 4.5 ns. Lines are terminated with 27 ohm resistors.



(a) Waveforms at Terminals 1 and 3

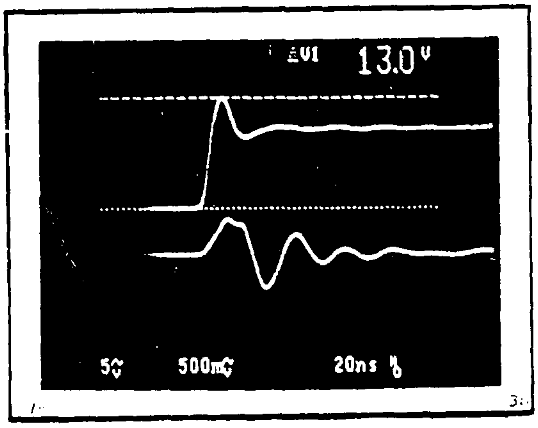


(b) Crosstalk Waveforms at Terminals 5 and 7

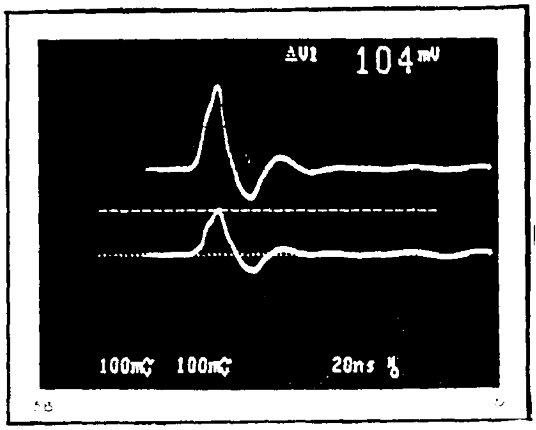


(c) Crosstalk Waveforms at Terminals 9 and 11

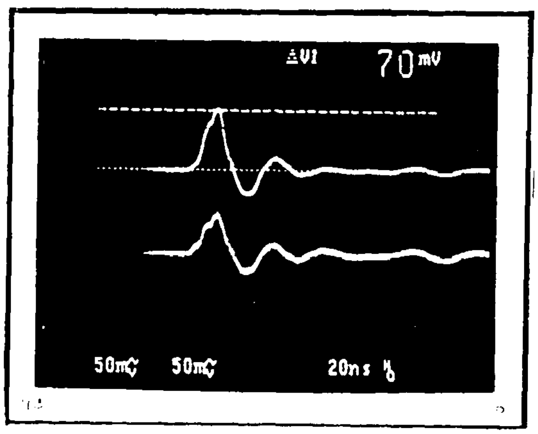
Figure 26. Observed crosstalk waveforms of group 1. Line length = 2 feet; line spacing = 54.5 mils; rise time = 4.42 ns. Conductors 4, 6, 8, 10 and 12 are short circuited at the far end.



(d) Waveforms at Terminals 1 and 3

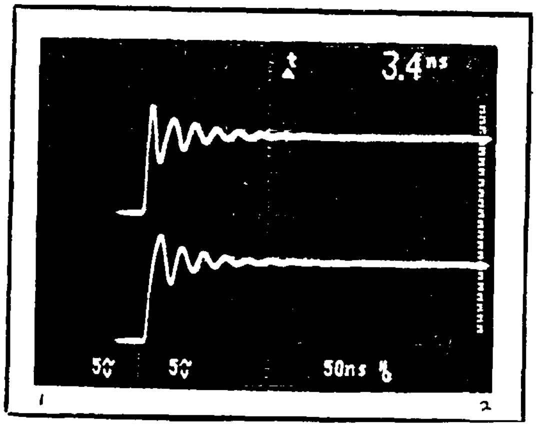


(e) Crosstalk Waveforms at Terminals 5 and 7

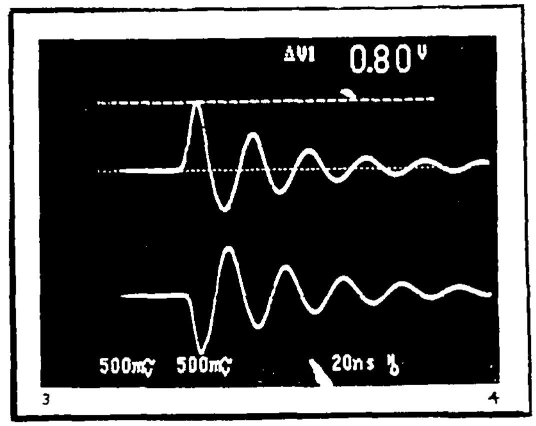


(f) Crosstalk Waveforms at Terminals 9 and 11

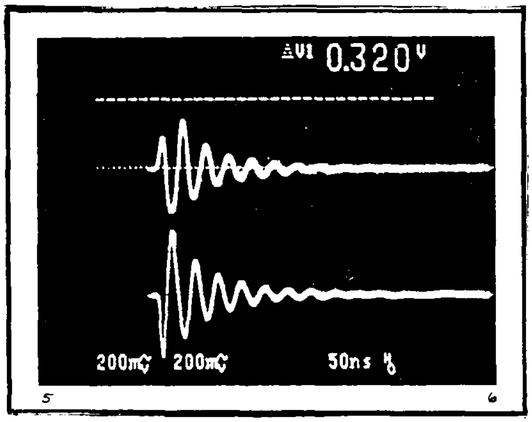
Figure 26 (cont). Observed crosstalk waveforms of group 2. Line length = 2 feet; line spacing = 109 mils; rise time = 4.42 ns. Conductors 4, 6, 8, 10 and 12 are short circuited at the far end.



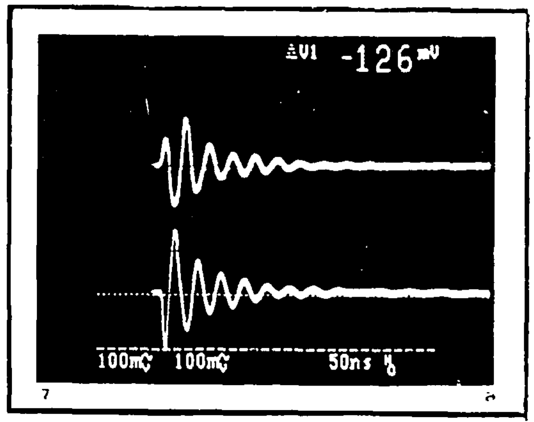
(a)Waveforms at Terminals 1 and 2



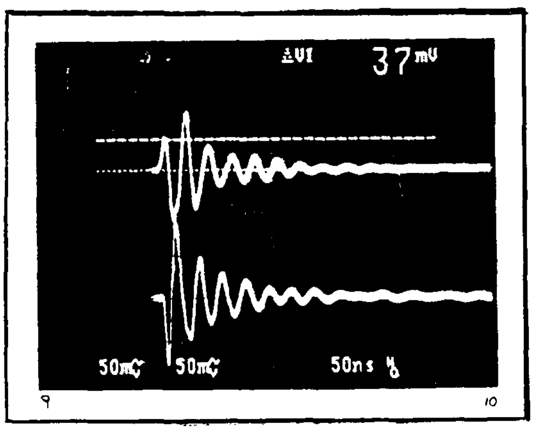
(b)Crosstalk Waveforms at Terminals 3 and 4



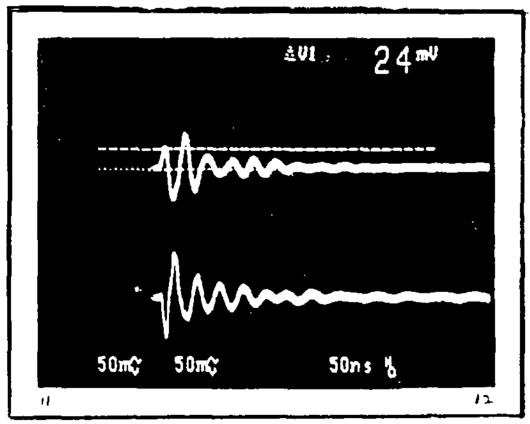
(c)Crosstalk Waveforms at Terminals 5 and 6



(d)Crosstalk Waveforms at Terminals 7 and 8



(e)Crosstalk Waveforms at Terminals 9 and 10



(f)Crosstalk Waveforms at Terminals 11 and 12

Figure 27. Observed crosstalk waveforms of group 1. Line length = 2 feet; line spacing = 54.5 mils; rise time = 4.42 ns. Conductors 4, 6, 8, 10 and 12 are open circuited at the far end.

Table 12. Measured voltages showing the effect of mismatch termination to the magnitude of crosstalk.

Terminal Number	R = 50 Ohms	R = 27 Ohms	R = 0 Ohm	R = ∞ Ohm
1	14 V	14 V	14 V	14 V
2	14 V	14 V	-----	14 V
3	840 mV	840 mV	710 mV	800 mV
4	-440 mV	-640 mV	-----	-660 mV
5	184 mV	218 mV	250 mV	200 mV
6	-164 mV	-184 mV	-----	-290 mV
7	82 mV	100 mV	116 mV	66 mV
8	-56 mV	-68 mV	-----	128 mV
9	46 mV	57 mV	71 mV	37 mV
10	-25 mV	-39 mV	-----	-77 mV
11	30 mV	36 mV	51 mV	24 mV
12	-15 mV	-26 mV	-----	-47 mV

As discussed, if the characteristic resistance of the line does not match the load resistance, the signal in the line is reflected. The reflected signal will continue to bounce back and forth between the ends of the active signal line, gradually decreased in amplitude by reflection coefficients and if the line is lossy, by the resistance in the line. This reflection process creates ringing in the active line and coincidentally adds to the severity of the crosstalk problem as shown in table 12. When the terminating resistors were replaced by 27 ohms or zero ohm, the magnitude of the backward and forward crosstalks increases significantly. It is also interesting to note from this experiment that when the far end was open circuited, the magnitude of the forward crosstalk increased while the backward crosstalk decreased.

SUMMARY AND CONCLUSIONS

The analysis of crosstalk between parallel conductors has been presented. Forward crosstalk and backward crosstalk equations provide the means for estimating crosstalk in a microstrip transmission line. A series of experiments were performed and shown to provide useful information and insight into the problem of crosstalk. The validity of the model's crosstalk predictions has been assessed through a comparison with the experimental results. Good agreement exists between calculated and measured results. Based on the close agreement between measured and predicted crosstalk values, this study has shown that the magnitude of crosstalk is a function of line spacing, signal rise time, signal amplitude, line length, line geometry, and circuit board geometry. The experiment has also shown that severe crosstalk problems may result from reflection, due to the mismatch of line characteristic impedance and termination.

The results of the experiment could prove useful for digital system design as a predictor of crosstalk. The equations, computer program listing, and graphs shown in this study could be useful design aids for printed circuit boards or other specific design application.

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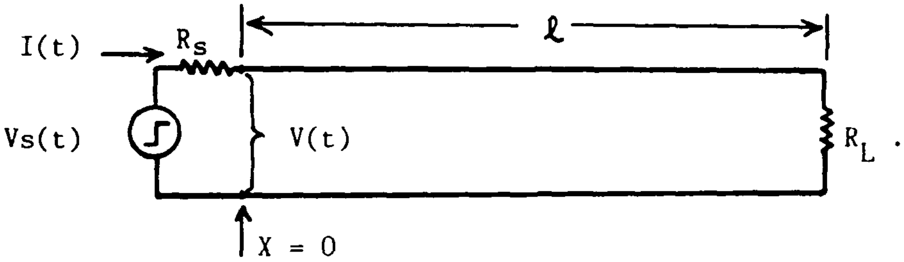
APPENDIX A

MATHEMATICAL DERIVATIONS

APPENDIX A1

Derivation of the Voltage at the input end at time $\frac{2\ell}{\mu}$



At X=0: $V_s(t)-I(t)R_s = V(t) = V^+(t)+V^-(t)$ (1)

$$I(t) = I^+(t)+I^-(t)$$

$$= \frac{V^+(t)}{R_o} - \frac{V^-(t)}{R_o} \quad . \qquad (2)$$

At X=0 and $t = \frac{2\ell}{\mu}$

$$V_s(\frac{2\ell}{\mu}) - I(\frac{2\ell}{\mu})R_s = V^+(\frac{2\ell}{\mu}) + V^-(\frac{2\ell}{\mu}) \qquad (3)$$

$$I(\frac{2\ell}{\mu}) = \frac{1}{R_o}[V^+(\frac{2\ell}{\mu}) - V^-(\frac{2\ell}{\mu})] , \qquad (4)$$

substitute equation 4 into equation 3

$$V_s(\frac{2\ell}{\mu}) - \frac{1}{R_o}[V^+(\frac{2\ell}{\mu}) - V^-(\frac{2\ell}{\mu})]R_s = V^+(\frac{2\ell}{\mu}) + V^-(\frac{2\ell}{\mu}) \ .$$

Solving for $V^+(\frac{2\ell}{\mu})$

$$V_s(\frac{2\ell}{\mu}) - \frac{V^+(\frac{2\ell}{\mu})}{R_o}R_s + \frac{V^-(\frac{2\ell}{\mu})}{R_o}R_s = V^+(\frac{2\ell}{\mu}) + V^-(\frac{2\ell}{\mu})$$

$$V_s(\frac{2\ell}{\mu}) + V^-(\frac{2\ell}{\mu})\frac{R_s}{R_o} - V^-(\frac{2\ell}{\mu}) = V^+(\frac{2\ell}{\mu}) + V^+(\frac{2\ell}{\mu})\frac{R_s}{R_o}$$

$$V^+(\frac{2\ell}{\mu})[1 + \frac{R_s}{R_o}] = V_s(\frac{2\ell}{\mu}) + V^-(\frac{2\ell}{\mu})[\frac{R_s}{R_o} - 1]$$

$$V^+(\frac{2\ell}{\mu})[\frac{R_o + R_s}{R_o}] = V_s(\frac{2\ell}{\mu}) + V^-(\frac{2\ell}{\mu})[\frac{R_s - R_o}{R_o}]$$

$$V^+(\frac{2\ell}{\mu})(R_o + R_s) = V_s(\frac{2\ell}{\mu})R_o + V^-(\frac{2\ell}{\mu})(R_s - R_o)$$

$$V^+(\frac{2\ell}{\mu}) = V_s(\frac{2\ell}{\mu})(\frac{R_o}{R_o + R_s}) + V^-(\frac{2\ell}{\mu})[\frac{R_s - R_o}{R_s + R_o}] \ .$$

APPENDIX A2

Laplace Transform of Traveling Wave on Line 2

Given the following equations

$$-\frac{\partial I_1}{\partial X} = C\frac{\partial V_1}{\partial t} \qquad (32)$$

$$-\frac{\partial V_1}{\partial X} = L\frac{\partial I_1}{\partial t} \qquad (33)$$

$$-\frac{\partial I_2}{\partial X} = C\frac{\partial V_2}{\partial t} - Cm\frac{\partial V_1}{\partial t} \qquad (34)$$

$$-\frac{\partial V_2}{\partial X} = L\frac{\partial I_2}{\partial t} + Lm\frac{\partial I_1}{\partial t}\ . \qquad (35)$$

Taking the Laplace transform of equations 32,33,34 and 35, we get

$$-\frac{\partial \mathcal{L} I_1}{\partial X} = sC\mathcal{L}V_1 \qquad (32a)$$

$$-\frac{\partial \mathcal{L} V_1}{\partial X} = sL\mathcal{L}I_1 \qquad (33a)$$

$$-\frac{\partial \mathcal{L} I_2}{\partial X} = sC\mathcal{L}V_2 - sCm\mathcal{L}V_1 \qquad (34a)$$

$$-\frac{\partial \mathcal{L} V_2}{\partial X} = sL\mathcal{L}I_2 + sLm\mathcal{L}I_1\ . \qquad (35a)$$

Differentiating equation 35a with respect to X,

$$-\frac{\partial^2 \mathcal{L} V_2}{\partial X^2} = sL\frac{\partial \mathcal{L} I_2}{\partial X} + sLm\frac{\partial \mathcal{L} I_1}{\partial X}\ . \qquad (35b)$$

Substituting equations 34a and 32a into equation 35b,

$$-\frac{\partial^2 \mathcal{L} V_2}{\partial X^2} = sL[-sC\mathcal{L}V_2 + sCm\mathcal{L}V_1] + sLm[-sC\mathcal{L}V_1]$$

$$= -s^2LC\mathcal{L}V_2 + s^2LCm\mathcal{L}V_1 - s^2LmC\mathcal{L}V_1$$

$$\frac{\partial^2 \mathcal{L} V_2}{\partial X^2} - s^2LC\mathcal{L}V_2 = s^2\mathcal{L}V_1[LmC - LCm]$$

$$= s^2\mathcal{L}V_1 LC[\frac{Lm}{L} - \frac{Cm}{C}]\ .$$

Since $LC = \frac{1}{\mu^2}$, then $\frac{\partial^2 \mathcal{L} V_2}{\partial X^2} - \frac{s^2\mathcal{L}V_2}{\mu^2} = \frac{s^2\mathcal{L}V_1}{\mu^2}\frac{Cm}{C}[\frac{CLm}{CmL} - 1]$

let $\gamma = \frac{Cm}{C}$ and $(\frac{C\ Lm}{Cm\ L}) = K$

then $\frac{\partial^2 \mathcal{L} V_2}{\partial X^2} - \frac{s^2\mathcal{L}V_2}{\mu^2} = \frac{s^2\mathcal{L}V_1}{\mu^2}\gamma[K-1]$.

APPENDIX A3

Forward Crosstalk Magnitude

Suppose $$Vf = -[\frac{\gamma(K-1)}{\mu}](\frac{\ell}{2})(\frac{dV}{dt})$$

since $\gamma = \frac{Cm}{C}$, $K = (\frac{Lm\ C}{L\ Cm})$ and $\mu = \frac{1}{\sqrt{LC}}$

then $$Vf = -\left[\frac{\frac{Cm}{C}(\frac{LmC}{LCm} - 1)}{\frac{1}{\sqrt{LC}}}\right](\frac{\ell}{2})(\frac{dV}{dt})$$

$$= -\left[\frac{Lm}{L} - \frac{Cm}{C}\right](\sqrt{LC})(\frac{\ell}{2})(\frac{dV}{dt})$$

$$= \left[Lm\frac{\sqrt{LC}}{L} - Cm\frac{\sqrt{LC}}{C}\right](\frac{\ell}{2})(\frac{dV}{dt})$$

$$= \left[Lm\sqrt{C}\ \frac{\sqrt{L}}{L}\ \frac{\sqrt{L}}{\sqrt{L}} - Cm\sqrt{L}\ \frac{\sqrt{C}}{C}\ \frac{\sqrt{C}}{\sqrt{C}}\right](\frac{\ell}{2})(\frac{dV}{dt})$$

$$= \left[Lm\frac{\sqrt{C}}{\sqrt{L}} - Cm\frac{\sqrt{L}}{\sqrt{C}}\right](\frac{\ell}{2})(\frac{dV}{dt})$$

since $Zo = \sqrt{\frac{L}{C}}$

then $$Vf = -\left[Lm\frac{1}{Zo} - CmZo\right](\frac{\ell}{2})(\frac{dV}{dt})$$

or $$Vf = \left[CmZo - \frac{Lm}{Zo}\right](\frac{\ell}{2})(\frac{dV}{dt}) .$$

APPENDIX A4

Suppose $Vf = [CmZo - \frac{Lm}{Zo}](\frac{1}{2})(\frac{dV}{dt})$ (43)

since the velocity of propagation $\mu = \frac{dX}{dt} = \frac{1}{\sqrt{LC}}$

we can then express ℓ as $\ell = \frac{T}{\sqrt{LC}} = \mu T$,

where $T = \ell\sqrt{LC}$, transit time for the transmission line

then $Vf = [CmZo - \frac{Lm}{Zo}](\frac{T}{\sqrt{LC}})(\frac{1}{2})(\frac{dV}{dt})$ (43a)

$$Vf = [\frac{CmZo}{\sqrt{LC}} - \frac{Lm}{Zo\sqrt{LC}}](T)(\frac{1}{2})(\frac{dV}{dt})$$

but $Zo = \sqrt{\frac{L}{C}}$

substituting to equation (43a)

$$Vf = [\frac{Cm\sqrt{\frac{L}{C}}}{\sqrt{LC}} - \frac{Lm}{(\sqrt{\frac{L}{C}})(\sqrt{LC})}](T)(\frac{1}{2})(\frac{dV}{dt})$$

$$= [Cm\sqrt{\frac{1}{C^2}} - \frac{Lm}{\sqrt{L^2}}](T)(\frac{1}{2})(\frac{dV}{dt})$$

$$Vf = [\frac{Cm}{C} - \frac{Lm}{L}](T)(\frac{1}{2})[\frac{dV}{dt}] \quad . \qquad (44)$$

APPENDIX A5

Backward Crosstalk Magnitude

Suppose $$Vb = \left[\frac{\gamma(K+1)}{2}\right]\left(\frac{V}{2}\right)$$

since $\gamma = \dfrac{Cm}{C}$, $K = \left(\dfrac{Lm}{L}\dfrac{C}{Cm}\right)$, and $\mu = \dfrac{1}{\sqrt{LC}}$,

then $$Vb = \left[\frac{\frac{Cm}{C}\left(\frac{Lm}{L}\frac{C}{Cm} + 1\right)}{2\,\frac{1}{\sqrt{LC}}}\right]\left(\frac{V}{2}\right)$$

$$= \left(\frac{V}{4}\right)\left[\frac{Lm}{L} + \frac{Cm}{C}\right]\sqrt{LC}$$

$$= \left(\frac{V}{4}\right)\left[Lm\,\frac{\sqrt{LC}}{L} + Cm\,\frac{\sqrt{LC}}{C}\right]$$

$$= \left(\frac{V}{4}\right)\left[Lm\sqrt{C}\,\frac{\sqrt{L}}{L}\,\frac{\sqrt{L}}{\sqrt{L}} + Cm\sqrt{L}\,\frac{\sqrt{C}}{C}\,\frac{\sqrt{C}}{\sqrt{C}}\right]$$

$$= \left(\frac{V}{4}\right)\left[Lm\,\frac{\sqrt{C}}{\sqrt{L}} + Cm\,\frac{\sqrt{L}}{\sqrt{C}}\right]$$

since $Zo = \sqrt{\dfrac{L}{C}}$

then $$Vb = \left(\frac{V}{4}\right)\left[\frac{Lm}{Zo} + CmZo\right].$$

APPENDIX B

PROGRAM LISTING

APPENDIX B1

(Program Listing)

```
C       Submitted by:  Juanito Del Rosario
C
C       Title of program: Microstrip Program
C
C
C       The FORTRAN program listed here determines the unknown values of the
C       characteristic impedance, the line width, the line thickness, or the
C       dielectric thickness of the microstrip transmission line.  It is
C       written in microstrip FORTRAN for the IBM compatible computer.
C
C
        INTEGER NUMSEL
        REAL  ER, A, Z0, w, h, t, SRVAL, LNVAL, LNRES, eVAL, wVAR, hVAR,
     +  tVAL
C
C       Definitions:
C
C       ER = dielectric constant
C       Z0 = characteristic impedance
C       w  = line width
C       h  = line thickness
C       t  = dielectric thickness
C
  500   WRITE(*,*)
        WRITE(*,*)
        WRITE(*,502)
  502   FORMAT(2X,'ENTER THE VALUE OF ER (nnnn.nnnn)')
        READ(*,510)ERVAL
  510   FORMAT(F9.4)
        ER = ERVAL
C
C
        SRVAL = ER + 1.41
        A = 87.0 / SQRT(SRVAL)
C
  700   WRITE(*,*)
        WRITE(*,*)
        WRITE(*,10)
   10   FORMAT(2X,'Use the number below to select the unknown variable.')
        WRITE(*,20)
   20   FORMAT(10X,'(1) FOR Z0')
        WRITE(*,30)
   30   FORMAT(10X,'(2) FOR w')
        WRITE(*,40)
   40   FORMAT(10X,'(3) FOR t')
        WRITE(*,50)
   50   FORMAT(10X,'(4) FOR h')
C
C
        READ(*,*)NUMSEL
        IF(NUMSEL.EQ.1)GO TO 60
        IF(NUMSEL.EQ.2)GO TO 70
        IF(NUMSEL.EQ.3)GO TO 80
        IF(NUMSEL.EQ.4)GO TO 90
```

```
C
C       *** SOLVING FOR Z0 ***
C
   60   WRITE(*,*)
        WRITE(*,*)
        WRITE(*,100)
  100   FORMAT(2X,'ENTER THE VALUE OF w (nnnn.nnnn)')

        READ(*,102)wVAL

  102   FORMAT(F9.4)

        w = wVAL

        WRITE(*,110)

  110   FORMAT(2X,'ENTER THE VALUE OF h (nnnn.nnnn)')

        READ(*,112)hVAL

  112   FORMAT(F9.4)

        h = hVAL

        WRITE(*,120)

  120   FORMAT(2X,'ENTER THE VALUE OF t (nnnn.nnnn)')

        READ(*,130)tVAL

  130   FORMAT(F9.4)

        t = tVAL

C

        CALL CHECVAL(w,h,ER,I,N)

        IF(I.EQ.1.AND.N.EQ.2)THEN

C

        LNVAL = (5.98*h) / ((0.8*w) + t)

        LNRES = ALOG(LNVAL)

        Z0 = A * LNRES

        WRITE(*,140)Z0

  140   FORMAT(2X,'Z0 = ',F9.4,2X,'OHMS')

        GO TO 600
```

```
      ELSE
      GO TO 900
      ENDIF
C
C     **** SOLVING FOR w ****
C
   70 WRITE(*,*)
      WRITE(*,*)
      WRITE(*,200)
  200 FORMAT(2X,'ENTER THE VALUE OF Z0 (nnnn.nnnn)')
      READ(*,202)Z0VAL
  202 FORMAT(F9.4)
      Z0 = Z0VAL
      WRITE(*,210)
  210 FORMAT(2X,'ENTER THE VALUE OF h (nnnn.nnnn)')
      READ(*,212)hVAL
      h = hVAL
  212 FORMAT(F9.4)
      WRITE(*,220)
  220 FORMAT(2X,'ENTER THE VALUE OF t (nnnn.nnnn)')
      READ(*,230)tVAL
  230 FORMAT(F9.4)
      t = tVAL
C
      eVAL = Z0 / A
      wVAR = (7.475 * h) / EXP(eVAL)
      w = wVAR - (1.25 * t)
```

```
C
      CALL CHECVAL(w,h,ER,I,N)
      IF(I.EQ.1.AND.N.EQ.2)THEN
C
      WRITE(*,240)w
  240 FORMAT(2X,'w = ',F9.4,2X,'INCHES')
      GO TO 600
      ELSE
      GO TO 900
      ENDIF
C
C     **** SOLVING FOR t ****
C
   80 WRITE(*,*)
      WRITE(*,*)
      WRITE(*,300)
  300 FORMAT(2X,'ENTER THE VALUE OF Z0 (nnnn.nnnn)')
      READ(*,302)Z0VAL
  302 FORMAT(F9.4)
      Z0 = Z0VAL
      WRITE(*,310)
  310 FORMAT(2X,'ENTER THE VALUE OF h (nnnn.nnnn)')
      READ(*,312)hVAL
  312 FORMAT(F9.4)
      h = hVAL
      WRITE(*,320)
  320 FORMAT(2X,'ENTER THE VALUE OF w (nnnn.nnnn)')
```

```
      READ(*,33Ø)wVAL
  33Ø FORMAT(F9.4)
      w = wVAL
C
      CALL CHECVAL(w,h,ER,I,N)
      IF(I.EQ.1.AND.N.EQ.2)THEN
C
      eVAL = ZØ / A
      tVAR = (5.98 * h) / EXP(eVAL)
      t = tVAR - (Ø.8 * w)
      WRITE(*,34Ø)t
  34Ø FORMAT(2X,'t = ',F9.4,2X,'INCHES')
      GO TO 6ØØ
      ELSE
      GO TO 9ØØ
      ENDIF
C
C     **** SOLVING FOR h ****
C
   9Ø WRITE(*,*)
      WRITE(*,*)
      WRITE(*,4ØØ)
  4ØØ FORMAT(2X,'ENTER THE VALUE OF ZØ (nnnn.nnnn)')
      READ(*,4Ø2)ZØVAL
  4Ø2 FORMAT(F9.4)
      ZØ = ZØVAL
      WRITE(*,41Ø)
```

```
  410  FORMAT(2X,'ENTER THE VALUE OF t (nnnn.nnnn)')
       READ(*,412)tVAL
  412  FORMAT(F9.4)
       t = tVAL
       WRITE(*,420)
  420  FORMAT(2X,'ENTER THE VALUE OF w (nnnn.nnnn)')
       READ(*,430)wVAL
  430  FORMAT(F9.4)
       w = wVAL
C
C
       eVAL = Z0 / A
       hVAR = ((0.8 * w) + t) / 5.98
       h = hVAR * EXP(eVAL)
       CALL CHECVAL(w,h,ER,I,N)
       IF(I.EQ.1.AND.N.EQ.2)THEN
C
       WRITE(*,440)h
  440  FORMAT(2X,'h = ',F9.4,2X,'INCHES')
       GO TO 600
       ELSE
       GO TO 900
       ENDIF
C
  600  WRITE(*,*)
       WRITE(*,*)
       WRITE(*,610)
```

```
  610  FORMAT(2X,'DO YOU WISH TO CONTINUE?')
       WRITE(*,620)
  620  FORMAT(6X,'ENTER "1" FOR YES (NO CHANGE ON ER VALUE)')
       WRITE(*,630)
  630  FORMAT(6X,'ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)')
       WRITE(*,640)
  640  FORMAT(6X,'ENTER "3" TO STOP THE PROGRAM')
C
       READ(*,*)NUMCONT
       IF(NUMCONT.EQ.1)GO TO 700
       IF(NUMCONT.EQ.2)GO TO 500
       IF(NUMCONT.EQ.3)THEN
       STOP
       ENDIF
C
  900  WRITE(*,*)
       WRITE(*,*)
       WRITE(*,*) 'THE VALUE OF w/h OR ER IS OUT OF RANGE!!'
       GO TO 600
       STOP
       END
C
       SUBROUTINE CHECVAL(w,h,ER,I,N)
       RATIO = w / h
       IF(RATIO.GE.0.1.AND.RATIO.LE.3.0)THEN
       I = 1
       ELSE
```

APPENDIX B1

```
I = Ø
ENDIF
IF(ER.GE.1.Ø.AND.ER.LE.15.Ø)THEN
N = 2
ELSE
N = Ø
ENDIF
RETURN
END
```

APPENDIX B2

(Sample Program Run)

```
cd fortran2

D:\FORTRAN2>for1

Microsoft FORTRAN77 V3.31 August 1985
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Source filename [.FOR]: strip
Object filename [strip.OBJ]:
Source listing  [NUL.LST]:
Object listing  [NUL.COD]:
 Pass One     No Errors Detected
             396 Source Lines

D:\FORTRAN2>pas2

 Code Area Size = #0ABB  ( 2747)
 Cons Area Size = #006C  (  108)
 Data Area Size = #08CC  ( 2252)

 Pass Two    No Errors Detected.

D:\FORTRAN2>link

Microsoft (R) 8086 Object Linker  Version 3.04
Copyright (C) Microsoft Corp 1983, 1984, 1985.  All rights reserved.

Object Modules [.OBJ]: strip
Run File [STRIP.EXE]:
List File [NUL.MAP]:
Libraries [.LIB]:

D:\FORTRAN2>strip


 ENTER THE VALUE OF ER (nnnn.nnnn)
4.7


 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
1


 ENTER THE VALUE OF w (nnnn.nnnn)
0.109
 ENTER THE VALUE OF h (nnnn.nnnn)
0.062
 ENTER THE VALUE OF t (nnnn.nnnn)
0.002
 Z0 =   50.1434  CHMS


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
```

```
1


 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
2


 ENTER THE VALUE OF Z0 (nnnn.nnnn)
50.0
 ENTER THE VALUE OF h (nnnn.nnnn)
0.062
 ENTER THE VALUE OF t (nnnn.nnnn)
0.002
 w =     .1095  INCHES


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
1


 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
3


 ENTER THE VALUE OF Z0 (nnnn.nnnn)
50.0
 ENTER THE VALUE OF h (nnnn.nnnn)
0.062
 ENTER THE VALUE OF w (nnnn.nnnn)
0.1095
 t =     .0020  INCHES


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
1


 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
4


 ENTER THE VALUE OF Z0 (nnnn.nnnn)
```

```
50.0
 ENTER THE VALUE OF t (nnnn.nnnn)
0.002
 ENTER THE VALUE OF w (nnnn.nnnn)
0.1095
 h =      .0620  INCHES


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
2


 ENTER THE VALUE OF ER (nnnn.nnnn)
9.4


 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
1


 ENTER THE VALUE OF w (nnnn.nnnn)
0.1095
 ENTER THE VALUE OF h (nnnn.nnnn)
0.062
 ENTER THE VALUE OF t (nnnn.nnnn)
0.002
 Z0 =    37.5799  OHMS


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
3
Stop - Program terminated.

D:\FORTRAN2>
```

APPENDIX B2

```
cd fortran2

D:\FORTRAN2>for1

Microsoft FORTRAN77 V3.31 August 1985
(C) Copyright Microsoft Corp 1982, 1983, 1984, 1985

Source filename [.FOR]: strip
Object filename [strip.OBJ]:
Source listing  [NUL.LST]:
Object listing  [NUL.COD]:
 Pass One     No Errors Detected
             396 Source Lines

D:\FORTRAN2>pas2

 Code Area Size = #0ABB  ( 2747)
 Cons Area Size = #006C  (  108)
 Data Area Size = #08CC  ( 2252)

 Pass Two    No Errors Detected.

D:\FORTRAN2>link




Microsoft (R) 8086 Object Linker  Version 3.04
Copyright (C) Microsoft Corp 1983, 1984, 1985.  All rights reserved.

Object Modules [.OBJ]: strip
Run File [STRIP.EXE]:
List File [NUL.MAP]:
Libraries [.LIB]:

D:\FORTRAN2>strip


 ENTER THE VALUE OF ER (nnnn.nnnn)
4.7
```

APPENDIX B2

```
 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
1


 ENTER THE VALUE OF w (nnnn.nnnn)
0.065
 ENTER THE VALUE OF h (nnnn.nnnn)
0.030
 ENTER THE VALUE OF t (nnnn.nnnn)
0.0015
 Z0 =    42.5854  OHMS


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
1

 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
2


 ENTER THE VALUE OF Z0 (nnnn.nnnn)
42.585
 ENTER THE VALUE OF h (nnnn.nnnn)
0.030
 ENTER THE VALUE OF t (nnnn.nnnn)
0.0015
 w =     .0650  INCHES


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM




1
```

```
 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
3

 ENTER THE VALUE OF Z0 (nnnn.nnnn)
42.585
 ENTER THE VALUE OF h (nnnn.nnnn)
0.030
 ENTER THE VALUE OF w (nnnn.nnnn)
0.065
 t =     .0015  INCHES

 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
2

 ENTER THE VALUE OF ER (nnnn.nnnn)
2.35

 Use the number below to select the unknown variable.
         (1) FOR Z0
         (2) FOR w
         (3) FOR t
         (4) FOR h
1

 ENTER THE VALUE OF w (nnnn.nnnn)
0.065
 ENTER THE VALUE OF h (nnnn.nnnn)
0.030
 ENTER THE VALUE OF t (nnnn.nnnn)
0.0015
 Z0 =    54.2860  OHMS
```

APPENDIX B2

```
 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
2


 ENTER THE VALUE OF ER (nnnn.nnnn)
4.7


 Use the number below to select the unknown variable.






          (1) FOR Z0
          (2) FOR w
          (3) FOR t
          (4) FOR h
1


 ENTER THE VALUE OF w (nnnn.nnnn)
0.055
 ENTER THE VALUE OF h (nnnn.nnnn)
0.100
 ENTER THE VALUE OF t (nnnn.nnnn)
0.0015
 Z0 =   90.6617  OHMS


 DO YOU WISH TO CONTINUE?
     ENTER "1" FOR YES (NO CHANGE ON ER VALUE)
     ENTER "2" FOR YES (TO CHANGE THE VALUE OF ER)
     ENTER "3" TO STOP THE PROGRAM
3
Stop - Program terminated.

D:\FORTRAN2>
D:\FORTRAN2>
```

APPENDIX C

SAMPLE CALCULATIONS

APPENDIX C1

CALCULATIONS OF FORWARD AND BACKWARD CROSSTALK (SEE TABLE 7 FOR REFERENCE)

Crosstalk calculation for group 1 with S1 = 0.0545", ℓ = 2 ft, rise time =4.5 ns V = 14 volts.

From figure 13, the forward crosstalk constant = $-[\frac{\gamma(K-1)}{\mu}]$ = 0.138 ns/ft.

Using Equation 30, $V_f = -[\frac{\gamma(K-1)}{\mu}][\frac{\ell}{2}][\frac{dV}{dt}]$

$$= -(0.138)(\frac{2}{2})(\frac{14}{4.5})$$

$$V_f = -0.43 \text{ volt.}$$

From figure 14, the backward crosstalk constant = $\frac{\gamma(K+1)}{2}$ = 0.184.

Using Equation 31, $V_b = [\frac{\gamma(K+1)}{2}][\frac{V}{2}]$

$$= (0.184)(\frac{14}{2})$$

$$= 1.2 \text{ volts.}$$

Similarly for group 2 with S2 = 0.109", ℓ = 2 ft, rise time = 4.5 ns, V = 14 volts.

From figure 13, the forward crosstalk constant = $[\frac{\gamma(K-1)}{\mu}]$ = 0.104 ns/ft.

Using Equation 30, $V_f = -[\frac{\gamma(K-1)}{\mu}][\frac{\ell}{2}][\frac{dV}{dt}]$

$$= -(0.104)(\frac{2}{2})(\frac{14}{4.5})$$

$$= -0.324 \text{ volt.}$$

From figure 14, the backward crosstalk constant = $\frac{\gamma(K+1)}{2}$ = 0.072.

Using equation 31, $V_b = [\frac{\gamma(K+1)}{2}][\frac{V}{2}]$

$$= (0.072)(\frac{14}{2})$$

$$= 0.50 \text{ volt.}$$

APPENDIX C2

CROSSTALK AS A FUNCTION OF INPUT SIGNAL (SEE TABLE 9 FOR REFERENCE)

Crosstalk calculation for group 1 with S1 = 0.0545", ℓ = 2 ft, rise time = 4.5 ns
V = 3.5 volts,

with $\frac{\gamma(K-1)}{\mu} = 0.138$ ns/ft

$$V_f = -\left[\frac{\gamma(K-1)}{\mu}\right]\left(\frac{\ell}{2}\right)\left(\frac{dV}{dt}\right)$$

$$= -(0.138)\left(\frac{2}{2}\right)\left(\frac{3.5}{4.5}\right)$$

$$= -0.107 \text{ volt}$$

with $\frac{\gamma(K+1)}{2} = 0.184$

$$V_b = \left[\frac{\gamma(K+1)}{2}\right]\left(\frac{V}{2}\right)$$

$$= (0.184)\left(\frac{3.5}{2}\right)$$

$$= 0.32 \text{ volt.}$$

Similarly, for group 2 with S2 = 0.109", ℓ = 2 ft, rise time = 4.5 ns, V = 3.5 volts,

with $\frac{\gamma(K-1)}{\mu} = 0.104$ ns/ft

$$V_f = -(0.104)\left(\frac{2}{2}\right)\left(\frac{3.5}{4.5}\right)$$

$$= -0.081 \text{ volt}$$

with $\frac{\gamma(K+1)}{2} = 0.072$

$$V_b = (0.072)\left(\frac{3.5}{2}\right)$$

$$= 0.126 \text{ volt.}$$

APPENDIX C2

CROSSTALK AS A FUNCTION OF INPUT SIGNAL (SEE TABLE 9 FOR REFERENCE)

Crosstalk calculation for group 1 with S1 = 0.0545", ℓ = 2 ft, rise time = 4.5 ns V = 7.0 volts,

with $$\frac{\gamma(K-1)}{\mu} = 0.138 \text{ ns/ft}$$

$$V_f = -\left[\frac{\gamma(K-1)}{\mu}\right]\left(\frac{\ell}{2}\right)\left(\frac{dV}{dt}\right)$$

$$= -(0.138)\left(\frac{2}{2}\right)\left(\frac{7}{4.5}\right)$$

$$= -0.214 \text{ volt}$$

with $$\frac{\gamma(K+1)}{2} = 0.184$$

$$= \left[\frac{\gamma(K+1)}{2}\right]\left(\frac{V}{2}\right)$$

$$= (0.184)\left(\frac{7}{2}\right)$$

$$= 0.644 \text{ volt.}$$

Similarly, for group 2 with S2 = 0.109", ℓ = 2 ft, rise time = 4.5 ns, V = 7 volts,

with $$\frac{\gamma(K-1)}{\mu} = 0.104 \text{ ns/ft}$$

$$V_f = -(0.104)\left(\frac{2}{2}\right)\left(\frac{7}{4.5}\right)$$

$$= -0.162 \text{ volt}$$

with $$\frac{\gamma(K+1)}{2} = 0.072$$

$$V_b = (0.072)\left(\frac{7}{2}\right)$$

$$= 0.252 \text{ volt.}$$

APPENDIX C2
CROSSTALK AS A FUNCTION OF INPUT SIGNAL (SEE TABLE 5 FOR REFERENCE)

Crosstalk calculation for group 1 with S1 = 0.0545", ℓ = 2 ft, rise time = 4.5 ns V = 10.5 volts.

From figure 13, $\frac{\gamma(K-1)}{\mu} = 0.138$ ns/ft.

Using equation 30, $V_f = -[\frac{\gamma(K-1)}{\mu}](\frac{\ell}{2})(\frac{dV}{dt})$

$$= -(0.138)(\frac{2}{2})(\frac{10.5}{4.5})$$

$$= -0.322 \text{ volt.}$$

From figure 14, the backward crosstalk constant = $\frac{\gamma(K+1)}{2} = 0.184$.

Using equation 31, $V_b = [\frac{\gamma(K+1)}{2}](\frac{V}{2})$

$$= (0.184)(\frac{10.5}{2})$$

$$= 0.96 \text{ volt.}$$

Similarly, for group 2 with S2 = 0.109", ℓ = 2 ft, rise time = 4.5 ns, V = 10.5 volts,

with $\frac{\gamma(K-1)}{\mu} = 0.104$ ns/ft

$$= -(0.104)(\frac{2}{2})(\frac{10.5}{4.5})$$

$$= -0.243 \text{ volt}$$

with $\frac{\gamma(K+1)}{2} = 0.072$

$$V_b = (0.072)(\frac{10.5}{2})$$

$$= 0.378 \text{ volt.}$$

APPENDIX C3

CROSSTALK AS A FUNCTION OF RISE TIME (SEE TABLE 11 FOR REFERENCE)

Crosstalk calculation for group 1 with $S_1 = 0.0545''$, $\ell = 2$ft, rise time = 48ns
V = 10 volts.

From figure 13, the forward crosstalk constant = $\frac{\gamma(K-1)}{\mu} = 0.138$ ns/ft.

Using equation 30, $V_f = -[\frac{\gamma(K-1)}{\mu}][\frac{\ell}{2}][\frac{dV}{dt}]$

$$= -(0.138)(\frac{2}{2})(\frac{10}{48})$$

$$= -0.0288 \text{ volt.}$$

From figure 14, the backward crosstalk constant = $\frac{\gamma(K+1)}{2} = 0.184$.

Using equation 31, $V_b = [\frac{\gamma(K+1)}{2}][\frac{V}{2}]$

$$= (0.184)(\frac{10}{2})$$

$$= 0.92 \text{ volt.}$$

Correction factor: $\frac{2\ell}{\mu t} = \frac{(2)(2\text{ ft})}{(5.77 \times 10^8 \text{ ft/sec})(48 \times 10^{-9} \text{ sec})} = 0.144$.

$$V_b(\text{corrected}) = (\frac{2\ell}{\mu t})(V_b) = (0.144)(0.92)$$

$$= 0.13 \text{ volt.}$$

Similarly, for group 2 with $S_2 = 0.109''$, $\ell = 2$ft, rise time = 48 ns, V = 10 volts,

with $\frac{\gamma(K-1)}{\mu} = 0.104$ ns/ft

$$V_f = -(0.104)(\frac{2}{2})(\frac{10}{48})$$

$$= -0.0217 \text{ volt}$$

with $\frac{\gamma(K+1)}{2} = 0.072$

$$V_b = (0.072)(\frac{10}{2})$$

$$= 0.36 \text{ volt.}$$

Correction factor: $\frac{2\ell}{\mu t} = 0.144$.

$$V_b(\text{corrected}) = (\frac{2\ell}{\mu t})(V_b) = (0.144)(0.36)$$

$$= 0.052 \text{ volt.}$$

APPENDIX C3

CROSSTALK AS A FUNCTION OF RISE TIME (SEE TABLE 11 FOR REFERENCE)

Crosstalk calculation for group 1 with $S_1 = 0.0545''$, $\ell = 2ft$, rise time = 500ns
V = 10 volts.

From figure 13, the forward crosstalk constant = $\dfrac{\gamma(K-1)}{\mu} = 0.138$ ns/ft.

Using equation 30, $Vf = -[\dfrac{\gamma(K-1)}{\mu}][\dfrac{\ell}{2}][\dfrac{dV}{dt}]$

$$= -(0.138)(\frac{2}{2})(\frac{10}{500})$$

$$= -\ 0.0028 \text{ volt.}$$

From figure 14, the backward crosstalk constant = $\dfrac{\gamma(K+1)}{2} = 0.184$.

Using equation 31, $Vb = [\dfrac{\gamma(K+1)}{2}][\dfrac{V}{2}]$

$$= (0.184)(\frac{10}{2})$$

$$= 0.92 \text{ volt.}$$

Correction factor: $\dfrac{2\ell}{\mu t} = \dfrac{(2)(2\text{ ft})}{(5.77 \times 10^{8}\text{ ft/sec})(500 \times 10^{-9}\text{sec})} = 0.0139.$

$$Vb(\text{corrected}) = (\frac{2\ell}{\mu t})(Vb) = (0.0139)(0.92)$$

$$= 0.0128 \text{ volt.}$$

Similarly, for group 2 with S2 = 0.109", ℓ = 2 ft, rise time = 500 ns, V = 10 volts,

with $\dfrac{\gamma(K-1)}{\mu} = 0.104$ ns/ft

$$Vf = -(0.104)(\frac{2}{2})(\frac{10}{500})$$

$$= -0.0021 \text{ volt}$$

with $\dfrac{\gamma(K+1)}{2} = 0.072$

$$Vb = 0.36 \text{ volt.}$$

correction factor: $\dfrac{2\ell}{\mu t} = 0.0139.$

$$Vb(\text{corrected}) = (\frac{2\ell}{\mu t})(Vb)$$

$$= (0.0139)(0.36)$$

$$= 0.005 \text{ volt.}$$

END